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Experimental investigation of drilling fluid formulations and processing methods for a riser dilution approach to dual density drilling

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EXPERIMENTAL INVESTIGATION OF DRILLING FLUID FORMULATIONS AND PROCESSING METHODS FOR A RISER DILUTION APPROACH TO DUAL DENSITY DRILLING

A Thesis

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ABSTRACT

Oil and natural gas resources in the deepwater Gulf of Mexico are important for the U.S. economy, but development is limited by high costs. Dual density drilling concepts that result in wellbore pressure gradients similar to the natural subsurface gradients can simplify well designs and reduce costs.

Riser dilution may be an economical means of achieving such a system. This system would use a low density fluid to dilute the weighted wellbore fluid and give an intermediate density fluid in the riser. Two key concerns addressed in this study are whether a drilling fluid can be formulated that will suspend solids and transport cuttings after dilution and whether the fluid returning from the riser can be separated into wellbore and dilution fluids for a continuous process.

The first concern was addressed by laboratory testing of synthetic-base drilling fluids. The wellbore, riser, and dilution fluids were formulated with the same synthetic fluid to water ratio and liquid phase product concentrations with only the barite concentration, and therefore density, being different. Formulations with good emulsion stability over the maximum density range needed for real deepwater applications were developed. However, appropriate rheologies for the extreme case of 17.0 ppg wellbore fluid and 9.5 ppg riser fluid were not achieved with laboratory muds.

Separation testing was conducted to address the second concern using a laboratory centrifuge and hydrocyclones. The laboratory centrifuge demonstrated that practically all barite could be removed from the dilution stream and retained in a wellbore stream, but also that the wellbore stream rheologies were excessively high.

Hydrocyclone results implied the need for two stages of separation. The most successful two stage trial gave less contrast in densities than the laboratory centrifuge, but gave better rheologies and emulsion stabilities than either the laboratory fluid or the laboratory centrifuge tests. Also, the rheologies from hydrocyclone testing were only slightly less than the rheology values considered necessary for a working riser dilution system. Both the density contrast and the rheologies were also close to the best centrifuge results published by others working on similar systems.

1. INTRODUCTION

1.1 Natural Gas Reserves in Deepwater

Natural gas and its use, both industrial and residential, is a very important part of the U.S. economy. One area of potential in the search for new natural gas reserves is the deepwater portion of the Gulf of Mexico (GOM). Development of these deepwater natural gas resources is limited by the high capital costs involved. These costs are due to high drilling rig rates, increased drilling time for deepwater wells and an increased number of casing strings having to be set[1]. Consequently, the developments of some deepwater resources are rejected as being economically not feasible. In extreme cases, the ultimate objective is unreachable due to casing size limitations. These problems prevent some deepwater natural gas prospects from being drilled.

1.2 Dual Density Drilling as a Deepwater Drilling Solution

When drilling conventionally in deepwater, the riser annulus is filled with drilling mud of the same density as the wellbore. The mud density is selected to provide a wellbore pressure opposite the permeable zones in the open hole that is greater than the formation pore pressure. This difference in pressure prevents the flow of formation fluid into the well. However, the wellbore pressure opposite a given formation must be less than the formation fracture pressure to prevent fracture.

Deepwater Gulf of Mexico wells often encounter formations that have a narrow margin between the formation pore pressure and formation fracture pressure. This narrow margin is the result of abnormally high pore pressures, much greater than the pressure due to the hydrostatic gradient of water, and formation fracture pressures lower than that of shallow water formations due to a significant portion of the overburden being water rather than dense sediments. Because of these narrow margins, a greater number of casing strings are required compared to onshore wells of similar depths. The large number of casing strings required to protect the formation can be seen for an example 24,000 foot deep well in Figure 1.1.

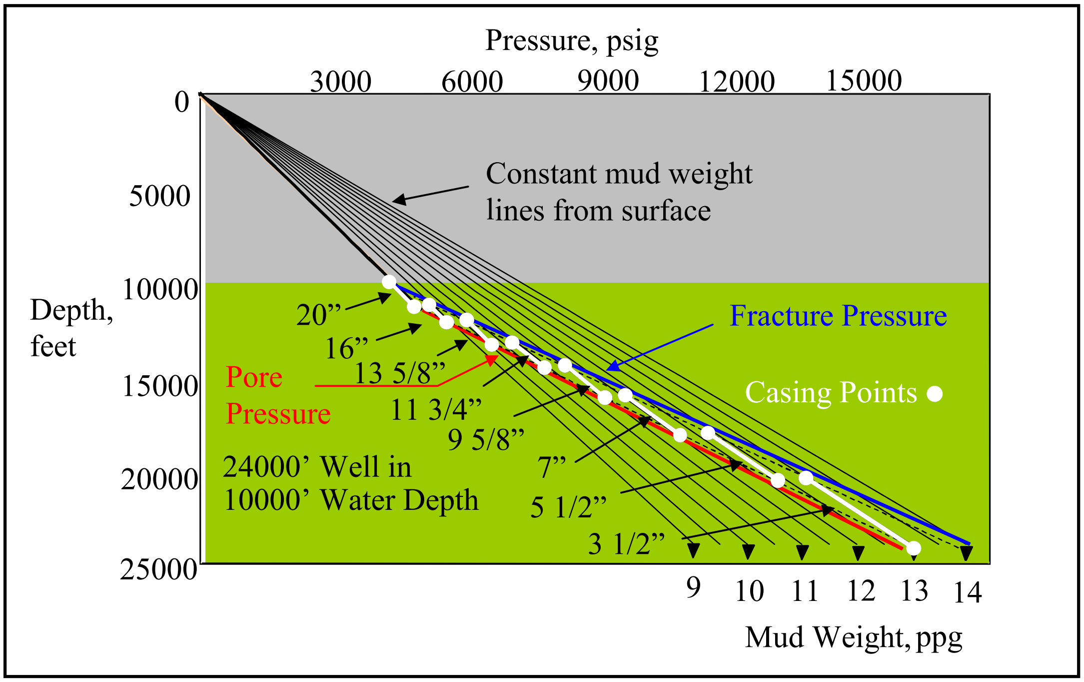

Figure 1.1 – Pressure versus Depth for Conventional Drilling[2]

One possible way to overcome these problems is with the use of a dual density drilling system or, as it is sometimes referred to, a “dual gradient drilling” system. This system uses two fluids with different density in the wellbore as opposed to the single density used in conventional drilling. These two fluids can give a more favorable pressure profile in the well compared to conventional drilling. Figure 1.2 shows how a dual density approach changes the overall pressure versus depth profile compared to conventional drilling with a single density fluid. This figure shows the pressure profile for drilling the last section of hole. It can be clearly seen that dual density drilling reduces the pressure profile to the left. This is what allows dual density drilling to drill deeper before setting casing, as compared to conventional drilling. This favorable pressure profile can reduce costs in deepwater drilling activity because it would reduce the number of casing strings needed and the danger involved with kick control.

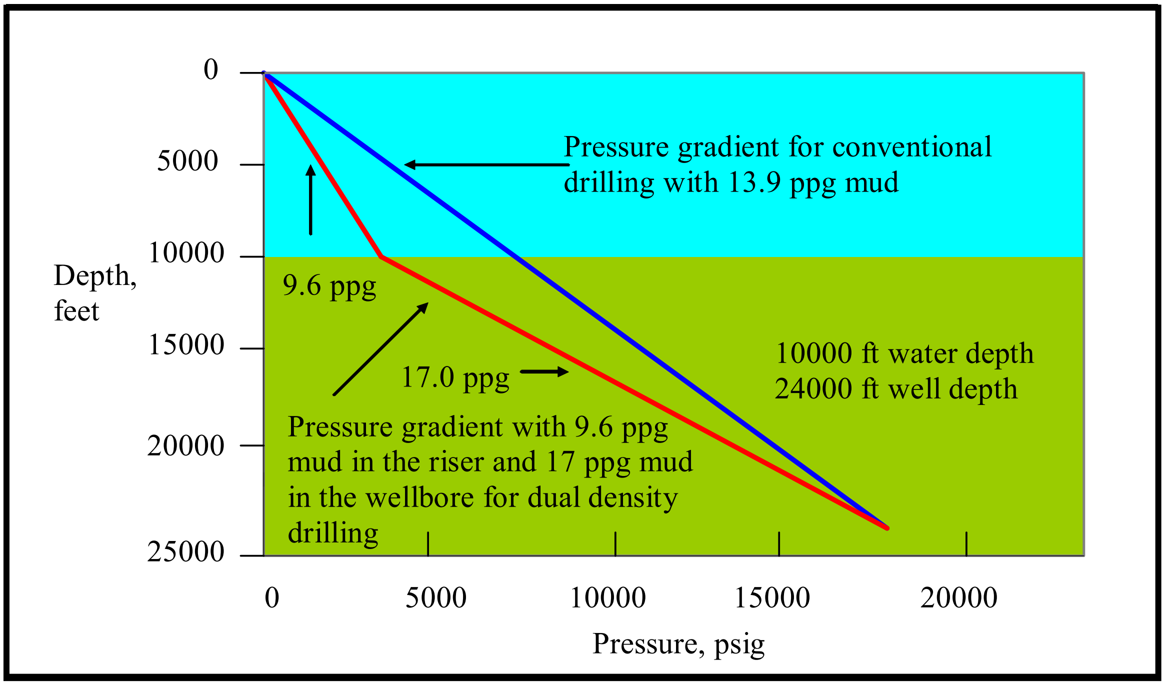

Figure 1.2 – Pressure Profiles for Dual Density Drilling and Conventional Drilling

This shift to the left in the dual density pressure profile is the result of the riser being full of fluid at 9.6 ppg that results from diluting the 17.0 ppg wellbore mud with a 7.6 ppg dilution mud at a 1 to 4 ratio. The 17.0 ppg mud in the dual density wellbore is needed to maintain the necessary bottomhole pressure, but is only present in the drillstring and subsea wellbore.

Figure 1.3 shows the same formation pressure versus depth profile as Figure 1.1 with the revised casing points expected with dual gradient drilling. Several systems have been proposed that utilize the dual density principle. The use of seafloor mudlift pumps[3,4,5,6,7,8,9], injection of hollow glass spheres into the riser[10,11], and the injection of gas or low density fluids into the riser[12,13,14,15,16,17,18] have all been advocated as possible means to create a dual density system.

The more favorable pressure profile is produced by having a low density fluid in the riser at or near the density of seawater and a higher density fluid, providing overbalance for the trip margin, in the wellbore. This arrangement produces two different fluid gradients in the well. This thesis is focused on one such system. It would inject a low density liquid into the riser at the seafloor. The wellbore fluid, which is of the highest density, flows through the drillpipe, the bit, and back up the wellbore annulus. The combination of these two streams gives the resultant riser fluid. This riser fluid is of a density between its two constituent fluids, but is of a reduced density as compared to a riser full of drilling fluid in conventional, single density drilling, that gives the same bottomhole pressure. This reduction in riser fluid density provides the benefits as outlined in the previous paragraph. The basic flow paths for such a system are shown in Figure 1.4.

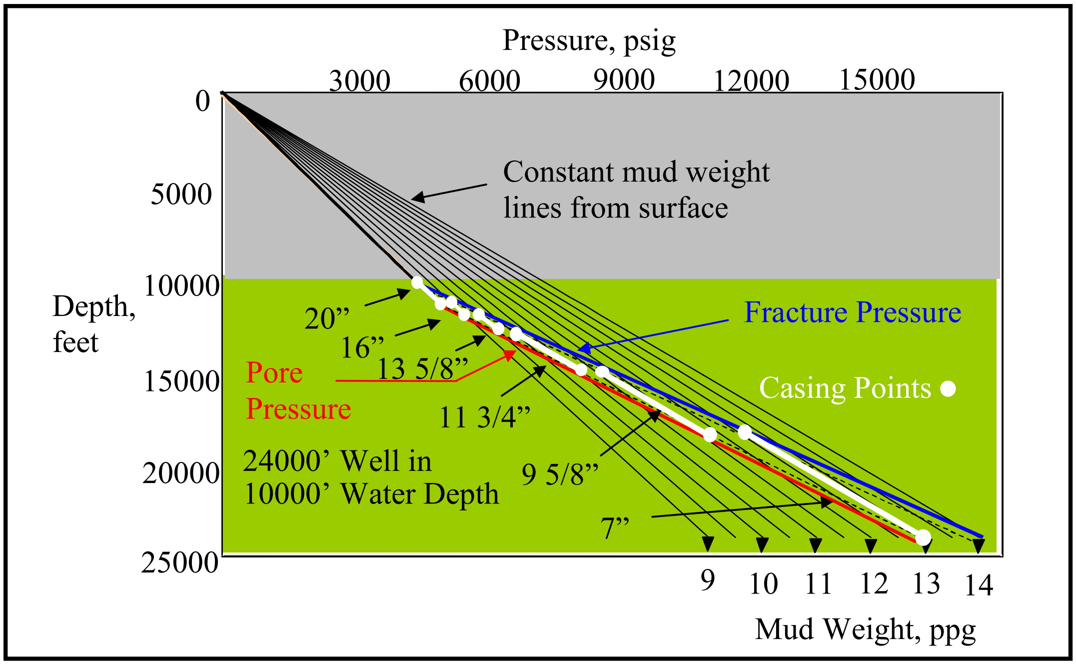

Figure 1.3 – Pressure versus Depth for Dual Density Drilling[2]

1.3 Project Objective

The injection of a low density liquid into the base of the riser to achieve to dual density drilling is referred to herein as “riser dilution.” The overall objective of this project is to determine if further research to investigate this approach is warranted. To make this determination, two essential questions need answering. First, can a drilling fluid be formulated that will effectively suspend solids and transport cuttings after heavy dilution with an unweighted dilution fluid? Second, can the drilling fluid returning from the riser be separated into wellbore fluid and dilution fluid on a continuous basis to sustain the necessary operation of the drilling fluid system? Earlier work by de Boer[13] showed that practical separation is possible using centrifuges. The focus of the separation research performed in this study is to examine if de Boer's efforts can be matched with the use of hydrocyclones.

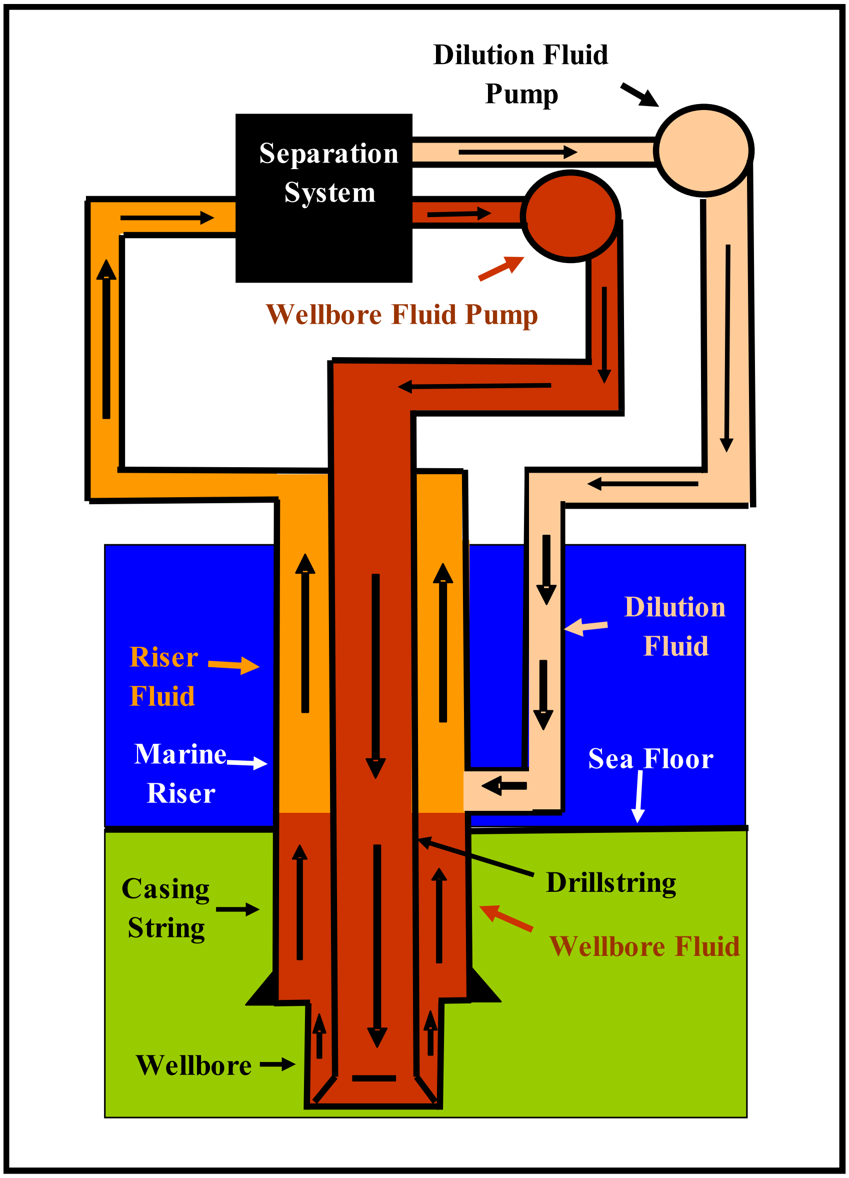

Figure 1.4 – Fluid Flow Paths for a Dual Density System Based on Riser Dilution

1.4 Use of the Terms “Drilling Fluid” and “Mud”

The term "drilling fluid" covers a wide range of fluids such as water-base drilling fluid, oil-base drilling fluid, synthetic-base drilling fluid, air, and even foam. This project focuses on synthetic-base drilling fluid or, as it is better known in the oil industry, synthetic-base mud (SBM). Drilling fluid will be referred to in this thesis as "mud." Any use of the term “drilling fluid” herein refers to SBM. There will be some instances of the use of the term "base fluid" which refers to unweighted SBM and the term "synthetic base fluid" which refers to the actual pure synthetic hydrocarbon liquid used to make SBM.

1.5 Description of Riser Dilution Project Work Plan

To determine if further research for the development of a riser dilution system is justified, the questions of dilution and separation from the project objective must be answered. To answer these questions, work was performed following the sequential plan as detailed below.

1. Review existing literature about dual density drilling, drilling fluids, and related technologies necessary to develop a riser dilution system.
2. Review candidate fluids to determine practical alternatives for use as a dilution fluid in a riser dilution system
3. Conduct laboratory work to develop a drilling fluid formulation, which satisfies the system needs in regards to density, rheology, emulsion stability and filtrate loss.
4. Perform laboratory work with a centrifuge to determine the degree of separation obtainable with a centrifuge.
5. Conduct experiments with various hydrocyclones to determine performance characteristics of the individual hydrocyclones.

6. Perform experiments to determine if two-stage processing with hydrocyclones is a practical alternative for a separation system for riser dilution.

1.6 Overview of Thesis

This first chapter introduces the problems that exist with current approaches to deepwater drilling for natural gas, the use of dual density drilling as a possible solution, the riser dilution approach to dual density drilling, work involved in this particular project, and the following description of this thesis.

Chapter 2 describes the dual density drilling system literature review carried out for this project.

Chapter 3 discusses the appropriate drilling fluid property specifications for a riser dilution system based on specifications provided by drilling fluids vendors and the formulation of a prototype drilling fluid system suitable for all of the subsystems in a riser dilution system. The examination of candidate dilution fluids is also included.

Chapter 4 presents the quantitative results from formulation and dilution testing of the prototype drilling fluid system.

Chapter 5 details the investigation of alternative means of achieving drilling fluid separation necessary for a riser dilution system. Experimentation was performed primarily with hydrocyclones. Some testing was also conducted using a lab centrifuge.

Chapter 6 presents the quantitative results from the separation testing of the prototype drilling fluid system presented in Chapter 5.

Chapter 7 gives the conclusions from this project and recommendations for further work towards a working riser dilution system.

2. DUAL DENSITY LITERATURE REVIEW

A literature review was performed to find and examine applicable references concerning various aspects of dual density drilling systems, drilling fluids, and other related technologies necessary for the development of a riser dilution system. The reviewed literature provided a basis for understanding the various aspects of dual density drilling, the necessary auxiliary systems, and operations. It also aided in determining where equipment and innovations from other projects could be implemented into a riser dilution system.

There are various types of systems under development in the pursuit of a commercially available dual density drilling system. The Dual Gradient Drilling System[12,13,14], developed by Luc de Boer, is the system that most closely resembles the work of this project. The literature on Mr. de Boer's system includes U.S. patents and a PowerPoint™ presentation. A similar system by Maurer Technology[10,11] involves the use of tiny hollow glass spheres (HGS) to reduce the density of the fluid column in the marine riser. This system is similar to our project in that it is a riser dilution approach to dual density drilling. The SubSea MudLift Drilling (SMD) Joint Industry Project (JIP)[3,4,5,6,7] is the only dual gradient system that has had a full scale, offshore field test, but has little in common with a riser dilution approach. It has been extensively described in industry and professional publications. Sub sea pumps are the key element of this system. The Deep Vision project[8,9] is similar to the SubSea MudLift JIP, but has not been discussed as much in the technical literature. The use of reeled pipe technology for drilling is an aspect peculiar to this system. Riser Gas Lift[15,16,17,18] is another approach for realizing a dual density system that has seen significant work here at L.S.U. and by Hermann. The system is similar to riser dilution, but it injects nitrogen gas into the riser at the seafloor to reduce the riser fluid density. This chapter presents a brief summary of the literature reviewed. The relevant concepts, technology, and literature that apply to this project are described.

2.1 DGS Dual Gradient Drilling System

Luc de Boer patented this system in 2003[12]. It is a riser dilution system that is essentially the same concept being investigated in this project. The system uses the drilling base fluid or the drilling base fluid emulsion as the low density fluid. This base fluid is injected through charging lines into the riser at the seafloor or below the seafloor. Adjustments to the injection rate are made, as necessary, to achieve a riser fluid density approximately equal to the density of seawater. According to de Boer[13], this system "allows the drilling mud to have a combined weight that keeps the bottom hole hydrostatic pressure above the formation pore pressure and below the formation fracture gradient at the last casing shoe for a much longer interval." Besides increasing the distance that can be drilled in an interval, the reduction in the density of the riser fluid gives a wellbore pressure profile that increases drilling safety margins. The high density drilling fluid and the injected base fluid are separated at the surface using centrifuges modified specifically for this system. Injection below the seafloor could increase the distance between casing points even further. This system does not require special subsea equipment. This absence of extensive and specialized subsea equipment is one of the DGS systems strengths.

The DGS system has yet to be commercially deployed. Extensive testing with various forms of oil-based drilling mud has been performed along with field-scale centrifuge separation testing. The inventor states that the DGS system can be operated on some 3rd and most 4th and 5th generation offshore drilling rigs without any or only minor modifications. The system uses standard drilling mud, drilling methods, and existing equipment familiar to the oil industry.

2.2 Hollow Sphere Dual Gradient Drilling

This is a system proposed by Maurer Technology[10,11]. It reduces the fluid density in the riser by the use of tiny hollow glass spheres (HGS) mixed into the low density fluid stream. This system is a riser dilution system in that it injects a low density fluid stream containing the HGS into the mud returning from the wellbore as it enters the riser at the seafloor. The fluid returning to the surface is processed through shale shakers with 100 mesh screens, which separate the spheres and cuttings from the drilling fluid. The spheres and cuttings are routed to a tank of seawater. The heavier rock cuttings then sink to the bottom and the spheres float to the top where they are gathered for further use. After passing through the shale shakers, a sufficient portion of the drilling fluid is then pumped back into the drillstring. The remaining amount of drilling fluid is mixed with the separated spheres to reconstitute the low density fluid stream. The reconstituted low density fluid stream is then pumped to the seafloor to be injected into the riser and continue the operating cycle. A Department of Energy project report[11] that is accessible on the Maurer Technology website gives details of this system.

2.3 The SubSea MudLift Drilling Joint Industry Project

The SubSea MudLift Drilling[3] (SMD) joint industry project (JIP) was led by Conoco-Hydril. This is the most researched, and written about, of all the dual density drilling projects. The SMD system gets its name from the sub sea pumping unit that is used to force the pressure inside the wellhead to be equal to the pressure of a column of seawater. It also lifts the drilling mud and cuttings through return lines outside of the riser to surface. The pumps in this system are diaphragm type and driven by seawater pressure provided by surface pumps. The subsea pumping rate is adjusted as necessary to control bottomhole pressure[4]. The riser is isolated from the well and filled with seawater.

An important piece of equipment from the SMD JIP[5] is the drillstring valve (DSV). This spring loaded valve is placed in the drillstring near the bottomhole assembly. The DSV was designed to limit the U-tubing effect due to the dense mud in the drillstring when the pump rate is reduced or stopped in the SMD system. Limiting the U-tubing helps prevent lost returns, especially when the well is shut in due to taking a kick.

A full scale prototype of this system has been field tested offshore, but is not known to be commercially available at this time. This system[5,6] has also been advocated as a possible approach to top-hole drilling.

2.4 The Deep Vision Project

This project has not been widely publicized and has much less available information compared to the SMD JIP. This approach to achieving a dual gradient system relies on seafloor pumps to control well pressure at the seafloor. Peculiar to the Deep Vision Project[8] is the use of reeled pipe technology for drilling and seafloor centrifugal pumps to return drilling mud and cuttings to the surface. The mud and cuttings are returned through lines outside of the marine riser. In this system, the riser is filled with seawater and separated from the well by a riser rotating control head[9]. The riser is used to deploy the stack and subsea pump system and to support control and power umbilical lines. The speed of the centrifugal pumps is manipulated with automation to control well bottomhole pressure. Conclusions on the work completed and the current project status are unknown.

2.5 Riser Gas Lift

This system is similar to riser dilution, but uses nitrogen gas as the low density fluid that is injected at the base of the riser. Riser gas lift was detailed extensively in a Ph. D. dissertation[15] at Louisiana State University by Lopes in 1997. The Lopes dissertation presents the results of a feasibility study on the use of an automated riser gas lift system used on a marine riser. The lift system is set up so that it would maintain a sub sea wellhead pressure that is the same as the surrounding seawater pressure. The control of abnormal formation pressures is to be provided by a weighted mud system in the wellbore.

Stanislawek[16,17] examined riser gas lift with the multi-phase flow simulator, OLGA™. Stanislawek programmed a mathematical model of mud and gas flow into OLGA™ to recreate the real well settings of Lopes. He then compared the results of his simulations to Lopes' results. This was done to evaluate and confirm the validity of OLGA™ for use in making determinations upon transients and multi-phase flow in a riser gas-lift system. Once the relevance of OLGA™ was verified, it was used to define gas requirements, the practical limits and develop well control methodology for a riser gas-lift system. This mathematical model can be further used independently to predict flow and pressure trends for various well control scenarios that could arise during riser gas-lift drilling operations.

Hermann[18] proposes a different form of riser gas-lift. This system would use smaller, high pressure, concentric risers to reduce the required volumes of gas. Hermann's system would also allow use of a surface blowout preventer stack.

3. DRILLING FLUID FORMULATION

The proper operation of a riser dilution system requires a drilling fluid that can suspend solids and transport drill cuttings effectively in both the wellbore and the riser. The drilling fluid used must be able to perform these functions even when heavily diluted with unweighted fluid. The goal of the work presented in this chapter was to address the first essential question from the project objective in Chapter 1: can a drilling fluid be formulated that will effectively suspend solids and transport cuttings after heavy dilution with an unweighted dilution fluid?

3.1 Type of Drilling Fluid

Synthetic-base muds (SBM) were selected as most representative of a practical dual density drilling mud based on their dominance as a drilling fluid for current deepwater Gulf of Mexico operations as indicated by both operators and mud suppliers. Baroid[19], and Baker Hughes[20] provided the most detailed recommended specifications for synthetic-base drilling muds. Tables 3.1 and 3.2 contain those mud property specifications for their SBM systems being utilized in Gulf of Mexico deepwater drilling operations. The gel strengths listed in Table 3.2 are for 10 seconds, 10 minutes and 30 minutes, respectively.

Table 3.1 - Synthetic-base Mud Specifications Recommended by Baker Hughes

Mud Weight, lbs./gal.	Plastic Viscosity,cp	Yield Point, lb/100 sq. ft.	Emulsion Stability, Volts
10.5 to10.9	35 to 45	15 to 20	>400
10.9 to 14.1	45 to 55	12 to 18	>400
14.1 to 15.1	50 to 60	10 to 15	>500
15.1 to 15.2	50 to 60	10 to 15	>500
15.2 to 15.5	50 to 60	10 to 15	>500

Table 3.2 - Synthetic-base Mud Specifications Recommended by Baroid

Mud Weight, lbs./gal.	Plastic Viscosity,cp	Yield Point, lb/100 sq. ft.	Gel Strength, lb/100 sq. ft.	HTHP Fluid Loss
10.5 to10.9	35 to 45	15 to 20	8,15,18	<4 cc/30min
10.9 to 14.1	45 to 55	12 to 18	12,18,20	<4 cc/30min
14.1 to 15.1	50 to 60	10 to 15	15,22,25	<3 cc/30min
15.1 to 15.2	50 to 60	10 to 15	18,25,28	<3 cc/30min
15.2 to 15.5	50 to 60	10 to 15	20,28,31	<3 cc/30min

In addition, M.I. Drilling Fluids personnel, particularly Fred Growcock[21], provided the following recommended SBM property specifications, the first three of which apply primarily to cuttings suspension and transport:

- The 6-rpm viscometer reading should be 1.5 to 2.0 times the open hole diameter.
- Using the power law fluid rheology model, "n," the fluid behavior index, should be as low as possible and "k," the consistency index, should be as high as possible.
- The "Carrying capacity index" or CCI should be at least 1. CCI is calculated using the following equation:

  $$\text{CCI} = (\text{Annular Velocity}) \times (\text{Mud Weight}) \times (k) / 400000 \qquad (3.1)$$

  Where Annular Velocity is in units of feet/minute and Mud Weight is in pounds/gallon (ppg).
- The HTHP fluid loss should be less than 10cc/30 minutes at bottom hole temperature (BHT).
- The emulsion stability (ES) should be a few hundred volts and should not drop during operations.

The specification of these properties is important because they relate directly to the ability of the mud to accomplish the necessary functions of a mud system. The specifications relating to cuttings transport and barite suspension are especially important given the original question about whether those function can be achieved in a diluted riser fluid. The functionality related to each mud property is described below. A more complete explanation[22] is provided by M.I.

- Mud weight (M.W.) – The selection of mud weight is based on the wellbore pressure required to control the formation pressures encountered in the open hole without causing lost returns.
- Plastic viscosity (PV) – This property relates to the portion of flow resistance caused by mechanical friction. If the PV is excessive, the equivalent circulating density will be excessive. This results in an increased risk of lost returns.
- Yield point (YP) and Gel strengths (Gels) – If these properties are too high, the consequences will be the same as for high PV. If they are too low, the result will be poor cuttings transport and an increased potential for barite settling or sag.
- Emulsion Stability (ES) – This measurement gives an indication of how well the water phase is held in the overall emulsion with the synthetic base fluid. A high reading is an indication of a stable mud with a strong water-in-oil emulsion. Muds with poor ES tend to separate and stratify, especially during static conditions.
- High temperature, high pressure (HTHP) fluid loss – Filtrate loss is important because excessive filtrate loss can contribute to formation damage and differentially stuck pipe.

3.2 Alternative Dilution Fluids

The CRC Chemistry and Physics Handbook[23] and various websites on the Internet[24,25,26] were reviewed to identify if any organic or inorganic compounds could be of use for a dilution fluid. The examined liquids were judged according to density, boiling point, melting point, flammability, and other qualities. Liquids meeting the density, boiling point and melting point criteria were deemed possible candidates for the selection process. The desired ranges of values of dilution fluid properties are:

- Specific gravity equal to or less than 0.8. The practical requirement is for the fluid to have a density significantly less than water.
- That the fluid would be a stable liquid in the temperature range of 30 to 300 °F.

These are minimum standards. The density has to be low to sufficiently reduce the density of the fluid column in the riser. The low temperature mark is to ensure that a liquid does not turn into a solid in the riser. The high temperature mark is to ensure that the fluid will not vaporize when subjected to high end operating temperatures.

The first areas examined were inorganic compounds. No inorganic compounds were identified that met the temperature range and density requirements. Many of the inorganic liquids with the lowest densities also have very low boiling points. Many inorganic compounds are carcinogens and/or mutagens. Some are violently reactive with water and other compounds.

An examination of organic compounds produced some possible choices. This is reasonable considering that the base fluids in many drilling fluids are synthetic hydrocarbon compounds. Table 3.3 contains properties for three organic liquids and a base fluid for a representative SBM used offshore GOM.

Table 3.3 - Basic Properties of Potential Dilution Fluids

Organic Liquids			
Liquid	Density	Boiling Point, F	Flash Point, F
1-Decene	0.741 g/ml	338.9	118
Decane	0.73 g/ml	345.2	115
N-Nonane	0.71 g/ml	303.8	87.8
Synthetic-Base Fluid			
IO 1618	0.79 g/ml	545	>201

The boiling and flash points of the IO 1618 synthetic-base fluid are considerably better than those of the organic liquids. Also, the chosen type of synthetic-base mud uses the IO 1618 for base fluid. A system using unweighted mud with this base fluid would eliminate compatibility problems and potentially make a riser dilution separation system relatively simple. These benefits led to the choice of unweighted synthetic-base mud as the system dilution fluid.

3.3 Fluid Property Specifications

The mud specifications from Baker Hughes, M.I., and Baroid that are described in Section 3.1 were used as a basis for defining reasonable mud property specifications for a riser dilution system. The mud properties were selected to ensure that the fluids would be able to carry out their necessary functions in each section of the well.

Properties of the wellbore fluid were selected to keep the wellbore stable, suspend barite, clean the hole, be a stable emulsion, and minimize fluid loss. Similarly, the riser fluid properties were chosen such that it would suspend barite, clean the riser, be a stable emulsion, and be of lower density than the wellbore fluid. The required properties for the dilution fluid were to be a stable emulsion and provide the rheology and low density required for combination with the wellbore fluid to create the riser mud. Table 3.4 outlines the selected drilling fluid property specifications. NS stands for "Not Specified."

Table 3.4 - Mud Properties Desired for a Dual Density System

Mud Property	Wellbore Fluid	Dilution Fluid	Riser Fluid
Density, ppg	17.0	7.6	9.5
PV, cp	45 - 55	NS	15 - 25
YP, lbf/100 sq ft	15 - 25	NS	15 - 25
6-rpm reading	15 - 25	NS	8+
10 sec. Gel Str.	16 - 24	NS	8+
10 min. Gel Str.	18 - 26	NS	15+
ES, volts	>400	>340	>400
HTHP Fl. Loss	<10 cc/30 min	NS	NS

Three densities were initially selected for dilution testing to represent the wellbore fluid, the riser fluid, and the dilution fluid. A dilution ratio of 4:1 was chosen as the maximum practical ratio due to the flow rates and volumes that would be required to make such a system work. These densities were selected as explained below.

- Wellbore Fluid: 17.0 ppg - This is the maximum wellbore fluid density that would be needed in a dual density system if the riser is diluted with a 7.6 ppg fluid at a 4:1 ratio to give the bottom hole pressure required for the highest pressure example provided by industry.
- Dilution Fluid: 7.6 ppg - This is the density of the mud formulation with the synthetic base fluid, the desired 80:20 synthetic fluid to water ratio, and all of the other additives except barite. This is the lowest practical fluid density given the strategy described in Section 3.5.
- Riser Fluid: 9.5 ppg - This is the result of the mixing of the dilution fluid and the wellbore fluid at a 4 to 1 ratio. Some tests were also conducted at a 2 to 1 dilution ratio resulting in a 10.7 ppg riser fluid.

3.4 Measurement of Fluid Properties

The following tests were performed on the three fluids in an attempt to establish a base formulation that would meet the properties specifications as outlined in Table 3.4 for all three fluids. Figure 3.1 shows the equipment used to measure these mud properties: a mud balance, a Fann viscometer, an emulsion stability meter, and a high temperature high pressure, HTHP, fluid loss cell.

- Density determination – Performed as described by M.I.[22], page 3.52, using a mud balance.
- Viscometer readings – Performed as described by M.I.[22], pages 3.53 and 3.54 at rotational speeds of 600, 300, 200, 100, 6, and 3-rpm respectively. Gel strength readings

were taken at 10 second, one minute, 10 minute, and sometimes 30 minute with a Fann viscometer at 120°F. The 600 and 300-rpm readings provide the basis for PV and YP.

- Electrical stability – Performed as described by M.I.[22], page 3.57, using OFITE ESM-30A and Fann 23D emulsion stability meters.

Figure 3.1 - Equipment Used for Measuring Properties of Drilling Fluids

- Barite sag determination – Performed as closely in accordance with M.I.[22], pages 20 A.6 and 20 A.7, as our equipment allowed. This test was performed to determine the extent of barite sag after dilution of the mud to the density that would exist in the riser. This is a small-scale test that uses the viscometer to establish fluid movement and then samples mud from the bottom of the cup over time. These test conditions are intended to be analogous to operating conditions in the riser annulus during circulation. The test focuses on dynamic sag. The importance of examining sag in the riser mud is that the annular velocity and fluid rheologies are lower than in the wellbore, therefore the likelihood of barite sag is greatest in the riser annulus. Barite sag determinations are also relevant for the wellbore fluid. Comparison of barite sag in the riser mud versus the wellbore mud can also establish whether dilution to the riser density is causing a more severe sag problem than exists in a typical mud.

- High-Temperature, High-Pressure Filtration – Performed in accordance with M.I.[22], pages 3.9, 3.10 and 3.11, and with advice by Jack Guedry of M.I.[27], at 300ºF and 600 psig with an OFITE 175 ml high pressure/high temperature filter press.

3.5 Drilling Fluid Formulations

The drilling fluids were formulated following the concept of maintaining the same component proportions, except for barite, in each fluid. This strategy was chosen with the underlying goal of maintaining the same oil-water ratio and liquid phase product concentrations in all parts of the circulating system. If successful, this would mean that the surface processing system for a dual density system could potentially be very simple. It would only need to re-concentrate the barite from the diluted mud that returns from the riser into a side stream to provide a weighted mud for use in the wellbore while the barite-free stream would provide the dilution mud.

The concentration of each mud constituent was based initially on the M.I. specifications and communication with M.I. drilling fluids personnel, especially Fred Growcock. Over 40 tests were run on diesel oil-base and synthetic-base muds to arrive at the formulations reported below. The primary difficulty in determining an appropriate formulation resulted from our goal of having the relative proportions of materials in the fluid phase of the mud the same over the broad range of barite concentrations needed to give a mud weight range from 7.6 ppg to 17.0 ppg. The drilling fluids were formulated using the following methods.

The basis for synthetic base fluid required to formulate a given density mud is determined with equation 3.2.

$$base \quad fluid\left(\frac{ml}{lab \quad bbl}\right) = 350\left[\left(-0.0285xMud \quad Weight\right) + 0.9652\right] \qquad (3.2)$$

The equation gives the amount in milliliters of synthetic base fluid per lab barrel of mud given the desired mud weight expressed in ppg. Equation 3.2 is for mixtures with a synthetic base fluid to water ratio of 80:20 and was derived from a graph of data found in information provided by M.I. The base fluid for the drilling mud used in this project is a manufactured or "synthesized" hydrocarbon fluid named IO 1618. This fluid is an internal olefin that is a combination of $C_{16}H_{32}$ and $C_{18}H_{36}$. It is manufactured from pure ethylene. A synthetic base fluid to water ratio, SWR, of 80:20 was selected as a compromise between the high ratios desired for a heavily weighted mud and low ratios used for unweighted muds. Therefore, the volume of brine in each density mud was determined so that the volume of water used to formulate the brine would be approximately 20%, by volume, of the mixture of synthetic base fluid and water in the drilling fluid. For the 10.25 ppg calcium chloride brine used in this study, the volume of brine was equal to the volume of water necessary to satisfy the 80:20 SWR divided by 0.922. The 10.25 ppg brine is a 25%, by weight, solution of calcium chloride in water. This concentration of calcium chloride was selected based on recommendations in the M.I. reference material.

The amounts of constituents used in the samples described below were determined after examining results from the previous tests. Early tests experienced excessively high viscosity in the weighted mud. The amount of clay used in the final formulation was reduced to help remedy this problem. A wetting agent was added primarily to increase the preference of the solids to be wet by the synthetic base fluid. The wetting agent concentration was also determined from the results of previous experiments. An emulsifier was added to keep the water-in-oil emulsion stable and to keep solids oil-wet. A low shear rate viscosifier was included to raise the low shear rate viscosity to improve cuttings and barite suspension properties. This liquid must be added with specific amounts of lime. Therefore, lime was added to ensure that both the low shear rate viscosifier and the emulsifier performed as intended.

Table 3.5 contains the final project formulation, Formulation A, for a field barrel of wellbore fluid. The dilution fluid was constructed with the same formulation except it did not contain any barite. Barite, barium sulfate ($BaSO_4$), was the weighting material used to bring the density up to 17.0 ppg as needed for the wellbore fluid.

Table 3.5 - Formulation A for 17.0 ppg Wellbore Fluid

Component	Amount
Synthetic base fluid	0.483 bpb
Water	0.126 bpb
Lime	3.6 ppb
$Ca\ Cl_2$	14.74 ppb
Organophillic Clay	4.0 ppb
Emulsifier	5.0 ppb
Wetting agent	5.3 ppb
$Ba\ SO_4$	513 ppb
Low shear viscosifier	0.68 ppb

Formulation A was used for the remainder of the experimental work with minor variations. It was used exclusively for the hydrocyclone separation testing and with some variations for the centrifuge separation testing. The property specifications and drilling fluid tests outlined in this chapter were used to provide a measure of the quality of the chosen drilling fluid formulation and in the remainder of the project as a means for gauging the success of the separation testing. The ability to measure the success or failure of particular aspects of the testing associated with this project is critical in answering the important questions about the feasibility of riser dilution as an option in successful deepwater drilling for natural gas resources.

4. RESULTS OF TESTING DRILLING MUD FORMULATIONS

4.1 Drilling Mud Formulation Testing

Drilling mud that can effectively suspend solids, transport cuttings and remain stable after heavy dilution with an unweighted dilution fluid is necessary for the operation of a riser dilution, dual density drilling system. The mud to do this was formulated based on the concept of maintaining the same component proportions, except for barite, in each fluid. This concept was adopted in order to minimize the processing required to separate riser mud into wellbore and dilution muds.

Mud formulations were developed using the strategy described in Section 3.5. The mud densities used were 17.0 ppg, 7.6 ppg, and 9.5 ppg. 17.0 ppg was the maximum density wellbore mud that would be required to apply a dual density system in the example deepwater well provided by industry. 7.6 ppg is the density of a mud formulated without barite, which represents perfect removal of barite to create a dilution fluid. 9.5 ppg is the resultant density from a combination of wellbore mud and dilution mud at a 4 to 1 ratio to create a riser mud. These densities were chosen as described in Section 3.3

Formulation A, described in Section 3.5, was selected as providing the best wellbore properties from over 20 formulations tested. Table 4.1 compares the desired properties from Table 3.4 with measured properties from Formulation A, listed as "Form. A" in Table 4.1, and de Boer's 80/20 OBM tests for the wellbore, dilution, and riser mud streams. The riser mud was created by mixing dilution mud with wellbore mud at a 4 to 1 ratio. As can be seen in Table 4.1, when compared to the desired values, all Formulation A muds had satisfactory emulsion stability, ES, and plastic viscosity, PV. However, the wellbore mud had gel strength and 6-rpm readings that are somewhat lower than desired. The riser mud yield point, YP, gel strength and 6-

rpm readings were substantially lower than desired. The YP, 6-rpm reading and gel strengths are important because they affect barite suspension and cuttings transport. Increasing the 6-rpm reading and gel strength of the wellbore mud by the small amount needed is relatively simple. As discussed later, however, achieving the desired rheology in the equivalent riser mud is of greater difficulty. In addition, the HTHP fluid loss of the wellbore mud was very high. The use of a filtrate control material could potentially correct the high HTHP fluid loss.

Table 4.1 - Values for Desired Properties, Formulation A, and de Boer’s 80/20 OBM

Mud Stream	Wellbore Mud			Dilution Mud			Riser Mud		
Mud Property	D.P.	Form. A	D.B. OBM	D.P.	Form. A	D.B. OBM	D.P.	Form. A	D.B. OBM
Density, ppg	17.0	17.0	14.5	7.6	7.5	8.3	9.5	9.3	9.3
PV, cp	45 - 55	42	45	NS	9	20	15 - 25	15	32
YP, lbf/100 sq ft	15 - 25	21	20	NS	6	7	15 - 25	3	12
6-rpm reading	15 - 25	12	NS	NS	4	NS	8+	3	NS
10 sec. Gel Str.	16 - 24	12	NS	NS	4	NS	8+	3	NS
10 min. Gel Str.	18 - 26	12	NS	NS	4	NS	15+	5	NS
ES, volts	>400	756	NS	>340	435	NS	>400	491	NS
HTHP Fl. Loss, cc/30min	<10	26	NS	NS	NT	NS	NS	NT	NS

Legend
D.P.- Desired Mud Property Values
Form. A - Measured Formulation A Mud Properties
D.B. OBM - de Boer's 80/20 OBM Properties
NS - Not Specified   NT - Not Taken

The riser mud properties achieved by de Boer and reported in Table 4.1 after diluting a 14.5 ppg wellbore mud were much more suitable than those for Formulation A. This may be partially due to de Boer working with a lower density wellbore mud and therefore a smaller range of densities. Presumably, the smaller density contrast between riser mud and wellbore mud would mean that a similar liquid phase formulation would give a smaller, and more favorable, contrast in mud properties. Also, the dilution mud density is higher than the ideal density of a mud containing no barite. The exact mud formulations used by de Boer are unknown. Therefore, it has not been possible to duplicate his results. Although the YP of 12 in de Boer's riser mud is still low, the riser mud's properties are much more suitable than those of Formulation A and demonstrate that satisfactory riser mud properties can probably be achieved at least for intermediate density wellbore muds.

Table 4.2 shows a comparison of Formulation A with the measured properties of Formulation B, which is listed as "Form. B" in Table 4.2, for the three mud streams. Formulation B is essentially the same as Formulation A except that the emulsifier concentration was 3.0 ppb rather than 5.0 ppb.

Table 4.2 - Properties of Drilling Muds Using Formulation B

Mud Stream	Wellbore		Riser Mud		Dilution Mud	
Mud Property	Form. A	Form. B	Form. A	Form. B	Form. A	Form. B
Density, ppg	17.0	17.0	9.3	10.5	7.5	7.6
PV, cp	42	50	15	15	9	8
YP, lbf/100 sq ft	21	21	3	4	6	5
6-rpm reading	12	14	3	3	4	4
10 sec. Gel Str.	12	17	3	4	4	4
10 min. Gel Str.	12	24	5	6	4	5
ES, volts	756	624	491	407	435	345
HTHP Fl. Loss, cc/30min	26 cc	not taken	not taken	not taken	not taken	not taken

The wellbore mud properties of Formulation B are better than those of Formulation A. The results of Formulation B do not include a HTHP fluid loss measurement for the wellbore. Also, the riser mud was based on a 2 to 1 dilution ratio rather than a 4 to 1 ratio. This was done to examine the effect of a lower dilution ratio. The wellbore mud had good properties except for the 6-rpm reading, which was out of specification by only 1 lb. /100 sq. ft. However, the riser mud still has a low yield point, 6-rpm reading, and gel strengths. The emulsion stability of all muds was satisfactory. Formulation B performed less favorably over sustained testing than Formulation A. For this reason an adaptation of Formulation A was subsequently chosen over Formulation B for the separation testing.

4.2 Barite Sag Testing

Barite sag is a major concern in weighted synthetic-base muds. The rheology specifications are based on avoiding barite sag and settling problems. Although no quantitative specifications for barite sag were identified, the test described in Section 3.4 does provide a means to observe the severity of sag in a mud sample over time. Therefore, a viscometer sag test was performed on wellbore and riser muds using Formulation A. The results are shown in Table 4.3. The results show the change in the density of the mud over time while keeping a constant temperature and stirring with the viscometer rotor. The mud was sampled using a syringe with a small tube attachment. The syringe was weighed before and after drawing the sample to determine mud weight. Because a given mud density is required to control the well, excessive variations in mud density can lead to problems including stuck pipe, lost circulation, and well control problems.

The results of the barite sag tests on the riser mud were more complicated than expected. The density of the mud near the bottom of the cup initially decreased from 9.3 ppg to 8.9 ppg. This decrease occurred after being in the viscometer running at 600 rpm for about 5 minutes while warming the mud to 120ºF. This behavior contrasts with the expectation that any sag would increase the barite concentration and density near the bottom of the cup. The test was started three times to recheck this reading, and the results were the same each time. Apparently, the barite would tend to move laterally due to the rotation in the viscometer and collect on the walls before settling to the bottom of the cup. A second sample taken after continuing the test for 30 minutes at 100 rpm showed that the mud density in the bottom of the viscometer cup increased to 10.0 ppg. This increase confirmed that significant sag occurred over the total length of the test. This was expected based on the low YP and 6-rpm reading for the riser mud. It confirms that this riser mud formulation is unsatisfactory and requires additional development.

Table 4.3 - Viscometer Sag Results for Formulation A

Mud Sample	Initial M.W., ppg	M.W. of Bottom Sample after heating to 120 F at 600 rpm, ppg	M.W. of Bottom Sample after 30 minutes at 100 rpm, ppg	Change in M.W., ppg
Wellbore	17.1	17.1	17.6	0.5
Riser	9.3	8.9	10.0	1.1

The barite sag results for the wellbore mud were more satisfactory. There was no change in density during the first 5 minutes of the test as the mud was brought up to 120°F with the viscometer operating at 600 rpm. After an additional 30 minutes at 100 rpm, the mud density at the bottom of the cup had increased by 0.5 ppg to 17.6 ppg. It is unclear whether this degree of sag is critical. In any event, eliminating the sag would be desirable. It is possible to increase the rheology of the 17.0 ppg mud significantly and remain within specifications. Therefore, it should be possible to further reduce the sag tendencies of the wellbore mud while keeping satisfactory properties overall. In addition, a more advanced version[28] of the viscometer sag test has been identified. If the necessary apparatus to perform this test can be obtained, it should be possible to conduct more quantitatively meaningful tests.

4.3 Formulation C

A third formulation, Formulation C, was developed in an attempt to obtain a mud system with satisfactory properties for use in the riser. The YP and gel strength, see Table 4.4, were increased relative to Formulations A and B but were still less than desired. The YP was also less than reported by de Boer. This formulation was then used as a basis for dilution and wellbore muds. Adding barite in an attempt to reach the density necessary for a wellbore mud resulted in excessive rheology as shown in Table 4.4. Specifically, a 13.8 ppg wellbore mud based on this formulation has an YP of 41, which is significantly more than the YP of 20 reported by de Boer for a 14.5 ppg mud or the values recommended by Baroid or Baker Hughes for this density. Consequently, it was concluded that this formulation was too viscous to be suitable. Apparently, the specific products, formulations, and/or processing system used by de Boer provide a more favorable relationship between density and rheology than the formulations developed herein.

Table 4.4 - Comparison of Rheologies

Mud Property	de Boer OBM Riser Mud	Formulation A Riser Mud	Formulation C Riser Mud	Formulation C Wellbore Mud
Density, ppg	9.3	9.3	9.6	13.8
PV, cp	32	15	22	46
YP, lbf/100 sq ft	12	3	10	41
10 sec. gel	Not Given	3	7	20
10 min. gel	Not Given	5	8	24
ES, volts	Not Given	491	474	264

4.4 Summary

Formulation A was the best drilling mud from the laboratory phase of testing of more than 20 formulations. Formulation A mud properties for the riser mud such as YP, 6-rpm readings, 10 second and 10 minute gel strengths were substantially less than the desired values. Increasing values for the riser mud using the concept of maintaining product concentrations proved difficult because increasing the rheology in the riser mud increases the rheology of the wellbore mud to unusable levels as seen in the discussion of Formulation C.

Formulation A wellbore mud property values of PV and YP were satisfactory and of similar values to the desired property values. The values for the 6-rpm reading, 10 second, and

10 minute gel strengths were only slightly less than the desired values. Increasing these should be relatively simple. The HTHP fluid loss for the Formulation A wellbore mud at 26 cc/30 minutes exceeded the standard set forth in Table 3.4 of less than 10 cc/30 minutes. The use of a filtrate control material could potentially correct this. The emulsion stability for the wellbore, riser, and dilution muds of Formulation A was satisfactory. Testing for barite sag showed that the Formulation A riser mud also suffered more from barite sag than the wellbore mud.

In spite of Formulation A being the best choice from the laboratory testing, its properties overall are inadequate to perform as needed for a riser dilution system. Therefore at this point we have not developed a drilling fluid system that can suspend barite and transport cuttings as needed for a riser dilution separation system. Nevertheless, de Boer's results using muds with a smaller range of densities were much closer to desired mud properties, and the rheology and electrical stability of the muds in subsequent hydrocyclone testing, documented in Chapter 6, were also closer to meeting the desired values. Therefore this problem may not be as difficult to overcome as indicated in this chapter

5. SEPARATION TESTING PLAN

An effective riser dilution, dual density system requires that the fluid stream returning from the marine riser be separated back into useable high density wellbore and low density dilution muds. To be useable, these two separated fluids must have the required densities and have the necessary viscosity characteristics as described in Chapter 3. Separation must be accomplished in an economical and practical manner as well. Separation using both a lab centrifuge and various hydrocyclones was undertaken in this project with particular emphasis on the use of hydrocyclones. The goal of the work presented in this chapter was to address the second essential question from the project objective in Chapter 1: can the fluid returning from the riser be separated into usable wellbore fluid and dilution fluid on a continuous basis to sustain the necessary operation of the drilling fluid system?

5.1 Centrifuge Testing

Centrifuge testing was conducted to get an understanding of the degree of separation possible with this piece of equipment. The lab centrifuge used in testing was much smaller than field centrifuges used in the oil industry. The goal was to obtain general limits on separation achievable using a centrifuge and provide first hand insights into the centrifuge separation process to supplement the near full-scale tests already conducted by de Boer.

To put lab testing in the context of the field centrifuge process, an examination of the centrifugal force and residence time encountered by fluid in a field centrifuge is important. Tests with the laboratory centrifuge should match field centrifuge conditions as closely as possible to make the laboratory centrifuge tests comparable and relevant.

In order to determine the rotational speed and residence time used in a typical oilfield centrifuge, specifications of a Hutchison Hayes decanter centrifuge[29] are given in Table 5.1

below. The centrifugal forces in this field centrifuge vary from 908 to 2113 times the acceleration due to gravity. The laboratory centrifuge tests were designed to subject samples to similar centrifugal force and residence time values as they would see in an oilfield centrifuge.

Table 5.1 - Specifications for an Oilfield Centrifuge

Manufacturer:	Hutchison Hayes
Model:	HH 5500
Internal Fluid Volume:	Approx. 175 gallons
Rated Capacity at 9.5 ppg:	200 gpm
RPM and g-force:	2000 RPM, 908 g to 3050 RPM, 2113 g
Approx. Residence Time:	Approx. 53 seconds

5.1.1 Drilling Fluids Used in Centrifuge Testing

Three sets of centrifuge tests were conducted. These tests used two different drilling mud formulations. Both of the drilling muds[30] used were based on Formulation A with slight variations. The first variation, named Formulation A', consisted of drilling mud mixed in accordance with Formulation A with the addition of filtrate control material. Both Formulation A and Formulation A' are described in Table 5.2. The formulations are shown without barite. Barite was added to raise the average density to 9.5 ppg for all of the centrifuge tests. The formulations of the liquid phase without barite are given because barite content was varied in the subsequent tests with hydrocyclones. Formulation A with barite is shown in Table 3.5.

The second drilling mud formulation for centrifuge testing consisted of a portion of Formulation A' with additional viscosifier (11.2 lb/bbl) and lime (0.63 gal/bbl) to match rheology of an earlier mixture from the laboratory dilution testing named Formulation C. This second variation is referred to as Formulation C'. Formulation C' was tested to observe the results of centrifuge testing on a more viscous drilling mud. This particular investigation occurred in Test set #2. The drilling muds used in all tests were mixed with a synthetic base fluid to water ratio (SWR) of 80:20.

Table 5.2 - Liquid Phase Formulations A and A’ without Barium Sulfate

Formulation A		Formulation A'	
Component	Amount	Component	Amount
Synthetic Base Oil	30.47 gal.	Synthetic Base Oil	30.20 gal.
Water	7.95 gal.	Water	7.88 gal.
Lime	5.4 lb.	Lime	5.36 lb.
Ca Cl_2	22.1 lb.	Ca Cl_2	21.9 lb.
Organophillic Clay	6.0 lb.	Organophillic Clay	5.96 lb.
Emulsifier	0.99 gal.	Emulsifier	1.0 gal.
Wetting Agent	1.03 gal.	Wetting Agent	1.02 gal.
Low Shear Viscosifier	0.14 gal.	Low Shear Viscosifier	0.13 gal.
Filtrate Control	0.00 lb.	Filtrate Control	2.98 lb.

5.1.2 Tests Using a Basket Type Centrifuge

These tests were conducted using a basket type centrifuge in which the drilling mud was introduced at a steady flow rate from a holding tank into the center of the rotating basket of the centrifuge. Figure 5.1 shows the centrifuge used in this testing. The drilling mud was spun in the rotating basket at rotational speeds selected to represent field centrifuges. The rotation caused the barite and other heavier components of the drilling mud to gravitate towards the outer wall of the rotating basket whereas the lighter fluid was forced towards the center and top of the rotating basket. Figure 5.2 shows the top view of the centrifuge basket. Once the basket was full of drilling mud, the lighter fluid spilled into the stationary basket which drained through a plastic hose to the outside of the centrifuge. The dense liquid and solids were retained in the centrifuge rotating basket requiring the test to be stopped when it was filled up with solids. In most of the tests, flow was stopped before completely filling up the inner basket with solids.

Figure 5.1 - Basket Centrifuge

Figure 5.2 - View of the Top Opening of Centrifuge Basket

Figure 5.3 and 5.4 show the caked sediments, slurry and liquids collected in the centrifuge basket after the test was stopped. The caked sediments in these tests consisted mainly of barite and bentonite solids. The liquid consisted of slurry similar to the base fluid for synthetic-base mud (SBM) and a separated oil phase seen in the figures as clear yellowish liquid along the walls of the basket. The different drilling mud phases from the centrifuge roughly correspond to the various drilling mud streams for a riser dilution system. They are described here and will be discussed further in Chapter 6.

- Basket Slurry – This mixture corresponds to the wellbore drilling mud. It consists of the separated sediments and liquids trapped in the rotating basket.
- Basket Effluent – This liquid that escapes over the top lip of the rotating basket corresponds to the dilution mud.
- Remixed mud – This is the recombination of the basket slurry and the basket effluent. This mixture should be approximately equal in density to the initial feed mud. This mixture corresponds to the riser mud.

Figure 5.3 - View of Caked High Density Sediments and Centrifuge Basket Liquids

Figure 5.4 - Closer View of Caked High Density Sediments and Liquids

5.1.3 Summary of Centrifuge Tests

The laboratory testing using a basket type centrifuge consisted of three sets of tests. These tests used two different mixtures of drilling mud. The specifics of these tests are as follows:

- Test #1 - This set of tests used Formulation A' mud weighted to 9.5 ppg. The flow rate and centrifuge rpm were varied. The mud was dispensed from a holding container into an opening in the top lid of the centrifuge. The test conditions imposed various levels of g-forces and residence time on the drilling mud.
- Test #2 – This test used Formulation C' to examine the effects of the separation process on a mud with higher viscosity characteristics than Formulation A'. This test was carried out in a similar manner to the tests in test set #1. The test on this mud was run at approximately 500 RPM with a residence time of approximately 120 seconds. Rotational speed at the lower end of the previously tested range was selected because the density of the low density effluent was found to be relatively insensitive to the RPM. The maximum calculated g-force from this speed setting is approximately 39 g's.

- Test #3 - There were concerns regarding the previous two tests that the results were affected by the transient nature of the tests. The fluid samples from test #1 were affected by a variety of different speeds. In both of those tests, the rotating basket was empty when the test began and filled during the test. To overcome these transient effects in test #3, the basket of the centrifuge was completely filled with mud (¾ gallon) prior to starting the test. This test was also conducted at approximately 500 RPM. The average flow rate during this test was 0.28 gallons per minute. This test used a remixed mud obtained by mixing the light effluent and heavier basket slurry of the Formulation A' from the first test run to give a density of 9.3 ppg. The density of the remixed fluid was apparently lower than that of the initial formulation due to loss of barite in process of recovering barite from the centrifuge. The approximate residence time for this test was 120 seconds.

The results from all three of these tests are presented in Chapter 6.

5.2 Comparison between Centrifuge and Hydrocyclone Separation

Hydrocyclones are of particular interest in this project due to economic and operational footprint issues compared to centrifuges. For example, a 4" diameter hydrocyclone[31] can typically process 65 gallons per minute, whereas a 2" hydrocyclone is rated for 15 gallons per minute. A battery of 32, 4" diameter hydrocyclones can easily process a target volume rate of 2,000 gallons per minute. Such a system[32] takes up about 40 sq. ft. of floor area and weighs approximately 2,400 lbs.

In contrast, the decanting centrifuge presented in Section 5.1 can process a maximum of 230 gallons per minute. Nine of these centrifuges would be needed to process a target mud flow rate of 2000 gallons per minute. Considering that each centrifuge weighs around 8,200 lbs and needs a floor area of approximately 66 sq. ft., using centrifuges alone for separation of solids from riser mud will need approximately 600 sq. ft. of floor area and add 82,000 lbs to the weight. Further, since each centrifuge costs around $100,000, this would require an expenditure of $900,000 or equivalent rental cost. Based on comparative data for hydrocyclones and centrifuges, if banks of hydrocyclones, in series or parallel, can achieve the desired separation of solids from riser mud, they are likely to be much more cost effective, to take up much less floor-area, and to add less weight to the rig than centrifuges.

5.3 Hydrocyclone Testing

The objective of hydrocyclone testing is to ascertain the extent to which solids can be removed from the riser mud using hydrocyclones. Figure 5.5 shows the flow paths[33] through a hydrocyclone. The feed fluid enters the upper chamber of the hydrocyclone tangentially and the shape of the hydrocyclone imparts a spinning motion on the fluid. The heavier, denser components, which include solids, of the fluid stream are thrown toward the hydrocyclone wall and exit through the bottom opening, or "underflow outlet." The lighter fluid stream components exit out the top opening, or "overflow outlet."

The question to be answered here is: can hydrocyclones separate the returning riser mud into separate mud streams suitable for use as dilution mud and wellbore mud in a riser dilution, dual gradient drilling process?

This question was addressed by experimental testing with actual field hydrocyclones. A hydrocyclone test stand was constructed at the LSU well facility to perform the riser mud separation testing. The system consists of a centrifugal pump, main feed tank, 2" hydrocyclones, overflow (OF) tank, underflow (UF) tank and the associated piping and hoses. Figure 5.6 shows a schematic of the test apparatus.

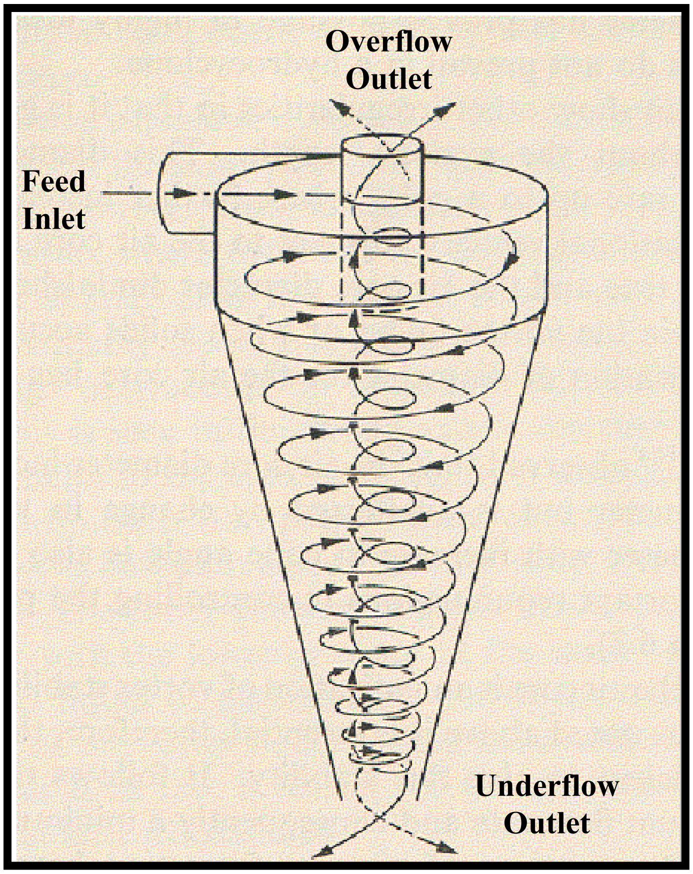

Figure 5.5 - Fluid Flow Paths in a Hydrocyclone[33]

The liquid phase used in all the hydrocyclone tests was mixed according to Formulation A shown in Table 5.2. Laboratory testing of this formulation indicated that it had the best mud emulsion stability and rheological characteristics over a wide range of densities when compared with other formulations. This formulation was tested in three states: unweighted base mud (without barite), weighted to 8.5 ppg, and weighted to 9.5 ppg. The 9.5 ppg density is expected to be representative of a practical riser mud for a dual density system. The 8.5 ppg density could be useful as a potential riser mud that might be needed in the shallow sections of some dual density well designs. The detailed results of evaluation and formulation are presented in a Gas Research Institute report[30] and Chapters 3 and 4 of this thesis.

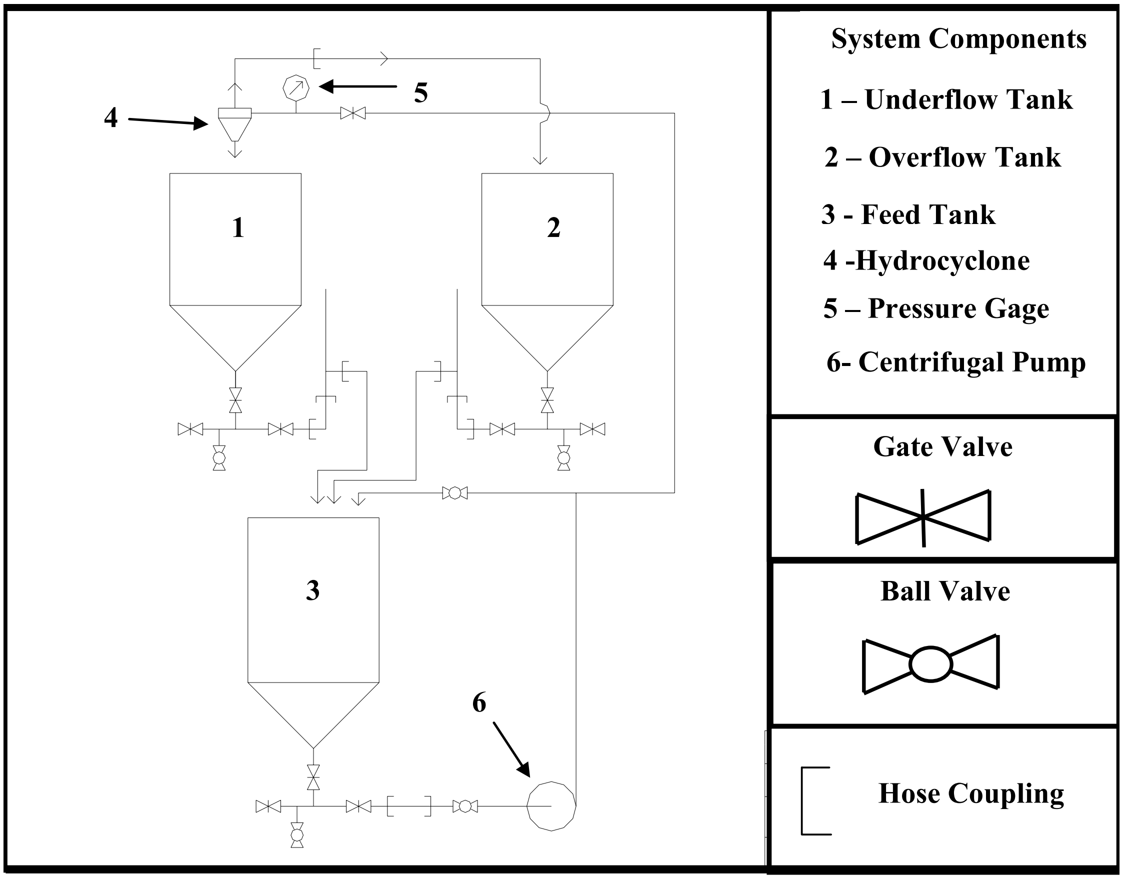

Figure 5.6 - Hydrocyclone Test Stand

5.3.1 Testing of 2" Clay Ejector Hydrocyclone

The first phase of testing was conducted on the unweighted Formulation A mud. The goal of this testing was to ensure the working of the test stand and to measure the variation of total, UF, and OF rates with head pressure for the selected SBM formulation. Figure 5.7 shows the actual test apparatus located at the L.S.U. well facility. Prior to all of the hydrocyclone tests, the test system was operated in the bypass mode to circulate and mix the mud to ensure homogeneity of properties as much as possible. The bypass mode bypasses the hydrocyclone and returns the feed mud from the pump discharge back to the feed tank.

Figure 5.7 - Hydrocyclone Test Stand at L.S.U. Well Facility

The system initially had all of the SBM (68 gallons) in the main feed tank. The centrifugal pump was started, and the mud processed through the hydrocyclone for a measured time duration with a controlled head pressure at the inlet to the hydrocyclone and with the drain valves from the UF and OF tanks closed. The pump was stopped when the feed tank had approximately 23 to 25 gallons remaining in it. The volume totals in the OF and UF tank were recorded. These readings allowed the calculation of volumetric flow rate and volumetric split through the hydrocyclone at each head pressure. The 2” clay ejector hydrocyclone is shown in Figure 5.8.

Figure 5.8 - 2” Clay Ejector Hydrocyclone

The next set of tests was conducted using continuous flow of mud through the hydrocyclone. The hydrocyclone test stand, as shown in Figure 5.6, is designed to have adjustable levels of fluid in the UF and OF tanks. The tanks were set to operate with relatively low levels and in a continuous, steady state manner. Flow was established through the hydrocyclone and system tanks until the levels were observed to be holding steady. At this point, the UF and OF drains were shut, a level was recorded, and the time was noted. The level changes over time in the UF and OF tanks were used to determine volumetric flow rate and flow split through the hydrocyclone.

The system could also be lined up to operate in steady state continuously. This was done by pumping the feed mud from the feed tank through the hydrocyclone. The UF and OF streams from the hydrocyclone were routed to their respective tanks and then returned to feed tank through the UF and OF tank drain lines on a continuous basis. Density measurements were taken on samples collected from the sample valves on the feed, UF, and OF tank drain piping. The levels of the tanks could also be observed and recorded over time.

The second phase of the 2” clay ejector hydrocyclone testing involved adding one sack, approximately 100 pounds, of barite to the unweighted Formulation A mud already in the system. The resultant mud density was 8.5 ppg. The hydrocyclone was now tested in the same manner as described on pages 40 and 41 to determine volumetric flow rate and volumetric split through the hydrocyclone at 38 and 50 psig head pressure. Steady state testing was also performed as described above. The primary purpose of these tests was to determine the performance of this hydrocyclone with the 8.5 ppg mud; this density is equivalent to seawater and therefore is the lowest density that is likely to be used for riser mud.

A third phase of tests was conducted after adding an additional 100 pound sack of barite to the mud, thus bringing the mud density to 9.5 ppg. The hydrocyclone was tested as described above at this mud weight. This particular mud density is the expected riser mud density for this project as described in Section 3.3. Therefore, this density was used for the majority of the hydrocyclone tests. The primary goal of these tests was to determine the performance of the hydrocyclone for separating the 9.5 ppg mud into wellbore and dilution streams with the desired properties.

The resultant data from hydrocyclone testing with both 8.5 and 9.5 ppg mud was used as spreadsheet input to assess UF and OF density as dependent variables of feed density. This was done to aid in determining how the 2” clay ejector hydrocyclone may fit into a practical separation scheme for a riser dilution, dual gradient drilling system.

Additionally, certain series of tests were carried out with both the 8.5 ppg and 9.5 ppg mud where either the OF or the UF was returned to the feed tank and recirculated while the drain was kept shut on the other tank that was not being recirculated. The intent of such recirculation tests was to understand the limits of the lowest and the highest densities achievable by the recirculation of OF and UF streams, respectively, through a hydrocyclone. These recirculation tests were also intended to give insights to the behavior of a multi-stage hydrocyclone separation.

The recirculation of the OF tank was performed first. The system was run with both UF and OF tanks recirculated until steady state conditions were achieved. Mud samples were collected from the feed tank and the OF tank, the UF drain was shut and time and UF tank level were recorded. After about three minutes, the feed and OF densities were almost equal, and the feed and OF mud samples were collected, and time and UF tank levels were recorded. Based on these tests, the change in the density of the recirculated, and therefore reprocessed, OF stream density was observed over time.

For the recirculation of UF tank, after re-establishing the steady state conditions, the valve positions were reversed from those of the previous tests, the mud from the UF tank was fed back to the feed tank, and the drain was shut on the OF tank. This test was intended to allow evaluation of the maximum density achievable for the UF stream. In this test, mud samples were collected from the feed tank and UF tank to determine feed and UF mud densities, and OF tank levels were recorded.

5.3.2 Testing of 2” Adjustable Hydrocyclone

A 2” hydrocyclone from Kem-Tron Technologies, Inc. was the next to be tested. This hydrocyclone, shown in Figure 5.9, has a removable UF tip to allow replacement due to wear and tear. This particular hydrocyclone was referred to as “adjustable” for the purposes of this project due to the ability to change the hydrocyclone UF diameter by changing the UF tip attachments. The initial testing of this hydrocyclone was conducted with the tip removed. This gave an UF diameter of 0.79”. The 9.5 ppg Formulation A mud, as used in the 2” Clay Ejector testing, was used in the testing of this hydrocyclone.

Figure 5.9 - 2” Adjustable Hydrocyclone with UF Tip Removed

Flow split testing and steady state testing was performed on this hydrocyclone in the same manner as performed with the 2” clay ejector hydrocyclone. The results from this testing were used to help determine tip sizes in later testing of this hydrocyclone with the tip installed.

The 2” adjustable hydrocyclone was further tested with the UF tip attached. One advantage to this device is the fact that the UF tip can be cut to give a desired UF opening diameter. This allowed the performance of different sizes of UF outlets to be analyzed. Extra tips were procured and cut to various sizes as needed.

The first tip size investigated in testing was 0.19”. This is the stock size of UF tip from the vendor. Flow split and steady state tests were performed using this tip size.

The next sizes tested were 0.27” and 0.37”. The original tip from the vendor was cut to these sizes for testing. Flow split and steady state testing were carried out to examine the hydrocyclones performance using each tip. The results from the testing of these tips along with the results from the tests with 0.19” and 0.79” tips were used to aid in choosing tip sizes for subsequent two stage testing.

5.4 Two Stage Processing of the 1st Stage UF Stream

To determine if further testing with a full-scale two stage separation system was justified, physical simulations of two stage separation were performed with two sequential single stage separations. This approach was deemed a practical way to make the determination. Data acquired from earlier testing was used to determine which hydrocyclone arrangements were to be used. The details of how these choices were made are presented in Chapter 6.

For the first test, the 2” adjustable hydrocyclone with a 0.44” UF tip was selected for the first stage. For the second stage of the first test, the 2” adjustable hydrocyclone was selected with a 0.63” UF tip. For the second test, the 2” clay ejector hydrocyclone was selected for the first stage and the 2” adjustable hydrocyclone with a 0.63” UF tip was selected for the second stage.

Flow split and steady state testing was conducted to examine the individual performance of the 2” adjustable hydrocyclone with both 0.44” and 0.63” UF tips using the 9.5 ppg Formulation A mud. The two stage separation tests were subsequently carried out. Both sets of tests were conducted in the same way except that the first stage hydrocyclones used for the two tests were changed as needed.

The simulated two stage test was started up in the bypass mode to mix the fluid in the feed tank. After sufficient bypass time to reach steady state conditions in the feed tank, samples were taken to determine the density of the feed mud. Then the system was shifted from the bypass mode to pumping through the hydrocyclone with the outlet valves of the UF and OF tanks shut. The feed tank was pumped down as far as practical, and the system was then shut down. The UF and OF tank levels were recorded, time measured, and density samples were taken from the UF and OF tanks. The OF and remaining feed tank fluids were removed from the system and placed in a holding tank. The UF fluid was then drained into the feed tank to be used as the feed fluid for the second stage.

At this point, the second stage hydrocyclone was installed into the system or the existing hydrocyclone UF tip was changed, as necessary. The system was then started up in the bypass mode to mix the mud in the feed tank. After sufficient bypass time, a sample was taken to measure the density of the second stage test mud now in the feed tank. Next, the system was lined up to pump through the hydrocyclone with UF and OF streams collected in their respective tanks. The feed tank was pumped as low as practical, and the time of pumping through the hydrocyclone was recorded. Levels of the UF and OF tanks were then recorded and samples drawn from the sample valves on each tank for density determination.

5.5 Intermediate Testing Using Various Tip Sizes

Additional UF tips were obtained and cut to various sizes for use in testing. This testing was performed to provide data for planning of further two stage processing of the first stage OF mud. The hydrocyclone was tested for flow split performance with 0.22", 0.255", and 0.274" UF tip sizes and steady state performance with the 0.274" UF tip. Figure 5.10 shows the different 2" adjustable hydrocyclone UF tip attachments, with tip opening sizes, from left to right, of 0.63", 0.44", 0.274", and 0.19".

Figure 5.10 - 2" Adjustable Hydrocyclone UF Tip Attachments

5.6 Two Stage Processing of the 1st Stage OF Stream – First Phase

After an examination of the results from the first phase of two stage testing, it was decided to conduct two stage processing of the OF stream from the first stage processing. Data acquired from earlier testing was used to determine the hydrocyclone arrangement to be used. The 0.274” and 0.19” UF tip sizes for the 2” adjustable hydrocyclone were chosen for this two stage processing.

To prepare for the test, the 0.274” UF tip was installed on the 2” adjustable hydrocyclone. The system was then started up to flow through the hydrocyclone with all fluids from the OF and UF tanks returning to the feed tank. The amount of UF fluid returning to the feed tank was then adjusted to achieve a steady state density in the feed tank equaling the initial density of 9.5 ppg. This was done by adjusting the UF tank drain valve. After sufficient time to approach steady state conditions in the feed tank, samples were taken to determine the density of the fluid in the feed tank. When the feed tank mud density was found to be holding steady at 9.5 ppg, the UF and OF tank densities were also measured. After the feed mud density, UF tank level at 4 gallons, and OF tank level at 25 gallons were all observed to be holding steady without adjustments for approximately 30 minutes, the UF and OF tank drains were shut and processing continued until approximately 55 gallons had accumulated in the OF tank when the pump was shut off. Density and temperature measurements were taken on mud samples from the feed, UF and OF tanks. The UF and remaining feed tank mud was removed from the system and placed in a holding tank. The OF mud was then drained into the feed tank to be used as the feed mud for the second stage.

At this point, the 0.19” UF tip was installed on the adjustable hydrocyclone for simulation of the second stage of processing. The system was started up in the same manner as was the first stage test with mud draining from both the OF and UF tanks into the feed tank. The UF tank drain valve was then adjusted to maintain the density in the feed tank equal to the density of the OF mud from the first stage, which was 8.5 ppg. When the feed tank mud density was found to be holding steady at 8.5 ppg, the UF and OF tank densities were also measured. After the feed mud density, UF tank level and OF tank level were observed to be holding steady without adjustments for approximately 30 minutes, the UF and OF tank drains were shut, and the pump was secured. Mud samples for density measurements were then taken from the UF and OF tank sample valves.

5.7 Two stage Processing of the 1st Stage OF Stream – Second Phase

This test was performed in a similar manner to the testing described in section 5.6. A few changes were made in the testing process in an attempt to improve the accuracy of the test. These differences include:

- Ball valves were installed to allow rapid closure of the UF tank and OF tank drain valves and hydrocyclone inlet valve at the end of the 30 minute steady state period. Rapid closure is necessary for two reasons. The first is that stray mud flow from the hydrocyclone after pump shutdown could corrupt density measurements taken on the mud in the UF tank. This stray after-flow from the hydrocyclone was observed on previous tests. The second reason is that the OF mud will be used for the feed mud in the second stage of processing. It is important that the OF and UF tank drain valves be closed essentially simultaneously to avoid a time period of returning only one of the UF or OF fluid streams to the feed tank which would result in the feed density and discharge densities changing from the steady state conditions and not being representative.
- At the end of the first stage of testing, the entire UF tank volume was drained into a five gallon bucket. Once the mud was in the bucket, it was mixed to ensure homogeneity. This was done to provide an accurate measurement of the UF density. This is important because the UF density was the most difficult density measurement to record accurately.

Also, the UF density is of extreme importance as this would be the wellbore mud in an actual system and its recorded value is used in calculations of test performance. The density of the mud in the UF tank at the end of the second stage of testing was determined in the same manner as was done for the first stage.

5.8 Testing of 4” Hydrocyclone

A very small amount of testing was performed with this hydrocyclone, shown in Figure 5.11. The testing was discontinued due to the volumes of the tanks used in the test stand being too small to handle the flow rates achieved through the 4” hydrocyclone.

Figure 5.11 - 4” Hydrocyclone

5.9 Summary

Lab scale centrifuge testing was performed to supplement the larger scale testing carried out by de Boer.

Testing to assess the performance of individual hydrocyclones and underflow tip sizes was conducted. The results from this testing were used to choose the best two stage combinations to separate the feed mud into usable wellbore mud and dilution mud on a continuous basis. Continuous separation is a practical necessity to sustain the operation of the dual density drilling fluid system. Processing of the first stage underflow and overflow was also assessed during the testing.

Testing of the 4” hydrocyclone was essentially impractical due to the limited size of the test system.

6. RESULTS OF SEPARATION TESTING

The second essential question presented in Chapter 1 to be answered was whether the drilling fluid returning from the riser can be separated into wellbore fluid and dilution fluid on a continuous basis to sustain the necessary operation of the dual density drilling fluid system. To answer this question, experimentation was conducted with a laboratory centrifuge, and hydrocyclones. The experiments were carried out in order to obtain information and insights that could answer this question regarding the feasibility of a functional dual gradient separation system. The effect of the separation process on the mud properties was also examined, which is important for answering the question of whether or not a functional drilling fluid, in terms of mud properties, can be formulated for a riser dilution system.

6.1 Centrifuge Test Results

Testing was done to determine if a centrifuge could split the riser mud into mud streams comparable to the necessary wellbore mud and dilution mud of a riser dilution, dual density drilling system. This testing supplements the nearly full scale testing performed by de Boer by investigating a wide range of g-force levels, residence times, and feed mud viscosities. The objectives were to determine the density contrast possible between the wellbore mud and the dilution mud, the resulting rheologies of the three mud subsystems, and also to examine the effect of elevated feed mud viscosity on the separation process.

6.1.1 Basket Centrifuge Separation of Original Riser Mud - Test #1

This set of tests was performed on the 9.5 ppg Formulation A' mud described in Section 5.1.1. The mud was dispensed from a holding container into the top opening of the basket centrifuge. Flow rate and centrifuge rpm were varied. Table 6.1 summarizes the flow rate, centrifugal force (g's), residence time, and final overflow (OF) effluent density measured during each test run.

Table 6.1 - Centrifuge Speeds and Mud Flow Rates for the First Set of Tests

Rotational Speed, rpm	g's	Q_{in}, gpm	Residence Time, sec.	Effluent Density, ppg
2500	965	0.43	128	7.4
2800	1210	0.11	497	7.1
1300	261	0.11	488	7.4
1850	528	0.58	95	7.4
1515	354	0.68	80	7.5
770	92	0.93	59	7.4

For all centrifuge speeds except 2800 rpm, the density of the effluent was essentially the same as for an ideal, unweighted, dilution mud and did not change significantly with rpm. To understand the changes in mud during the testing, viscometer and emulsion stability readings, shown in Table 6.2, were taken on the effluent mud stream as well as the dense liquid remaining in the centrifuge basket, and the mixture of this dense liquid with the separated solids, which is referred to as "basket slurry." The measured property values of the basket liquid and basket slurry in Table 6.2 represent the overall results after the tests were conducted.

Table 6.2 - Fluid Property Measurements for Separation of Original Riser Mud

Mud Property	Initial Test Mud	Basket Liquids	Basket Slurry	Effluent Mud	Remixed Mud
Density, ppg	9.5	12.1	16.2	7.4	9.3
PV, cp	16	40	89	9	16
YP, lbf/100 sq ft	5	18	50	4	4
6-rpm reading	3	9	19	4	3
10 sec. Gel Str.	3	7	16	3	3
10 min.. Gel Str.	5	10	Not Taken	4	4
ES, volts	285	236	266	411	359

Recombination of the mud components after centrifuge testing provided a basis for comparing the expected riser mud properties, here referred to as "remixed," to those of the original mud. The viscosity characteristics of original and remixed mud are essentially the same, but the emulsion stability increased in the remixed mud compared to the original mud.

In this first set of tests, the basket centrifuge was able to achieve separation to the extent that a density of 7.4 ppg was obtained for the effluent flow stream with some consistency. This device has characteristics that make it roughly similar, operationally, to the centrifuges used in oil field operations. Furthermore, the "basket slurry," formed by blending the liquids and solids left in the centrifuge had a density of 16.2 ppg, which is comparable to the density of the desired wellbore mud. Thus, the centrifuge was able to separate a simulated riser mud into a "dilution mud" of 7.4 ppg and a "wellbore mud" of 16.2 ppg.

The density contrast achieved was greater than that achieved by de Boer's results for an oil-base mud with an 80:20 oil to water ratio, as shown in Table 6.3. Nevertheless, de Boer's results do show better PV and YP values for wellbore, riser, and dilution muds. This may be attributed, in part, to de Boer's work having less of a density contrast between the riser mud and the wellbore mud. Results for 6-rpm reading, gel strengths, and emulsion stability were not reported for de Boer's work.

Table 6.3 - Comparison of Mud Properties from Test #1 to de Boer's Results

Mud Stream	Wellbore Mud		Dilution Mud		Riser Mud	
Mud Property	Form. A'	D.B. OBM	Form. A'	D.B. OBM	Form. A'	D.B. OBM
Density, ppg	16.2	14.5	7.4	8.3	9.3	9.3
PV, cp	89	45	9	20	16	32
YP, lbf/100 sq ft	50	20	4	7	4	12

Legend
Form. A' - Measured Formulation A' Mud Properties
D.B. OBM - de Boer's 80/20 OBM Properties

An important property to note is the low emulsion stability of the slurry left in the centrifuge basket. The riser mud, before being separated in the centrifuge, had a synthetic base fluid to water ratio (SWR) of 80:20 with an emulsion stability averaging 285 volts. However, the emulsion stability of effluent was higher than the original mud, at 411 volts, whereas that for the basket slurry was somewhat lower than the original mud, averaging 266 volts. Although, the SWR for effluent and basket slurry were not measured, the readings for electrical stability would indicate that more of the water had partitioned into the basket slurry as compared to the effluent. This is understandable based on higher density of the dispersed water compared to the continuous phase of synthetic base fluid. This creates a concern that centrifugal separation of riser mud may result in a less stable wellbore mud due the concentration of water in the heavier sediment and slurry in the centrifuge basket and the lighter synthetic base fluid concentrating in the lighter fluid phase near the center of the centrifuge basket and the centrifuge effluent fluid.

6.1.2 Basket Centrifuge Separation of Viscosified Riser Mud - Test #2

Test #2 was conducted using Formulation C'. This formulation is described in section 5.1.1 and contains a greater percentage of viscosifier than Formulation A'. The reason for adding a greater amount of viscosifier is that the viscosity and rheological properties of riser mud in the first centrifuge test were significantly lower than the desired properties of riser mud, as determined in Table 3.4. The basic rheological measurements for this viscosified mud are listed in Table 6.4. This mud was designated Formulation C' because it was made from Formulation A' mud that was modified to obtain properties similar to Formulation C, which is described in Section 4.3. Formulation C' did in fact achieve properties almost identical to that of Formulation C. The basket slurry from this test had a density of 16.0 ppg, an emulsion stability of approximately 330 volts, and was too viscous to test with a viscometer.

The most important observation from Table 6.4 is that the effluent separated from viscosified mud had much higher density, 8.7 ppg, than the effluent separated from the

Formulation A' in Test #1, which had density of 7.4 ppg. This difference in effluent densities is attributed to the elevated viscosity of the Formulation C' mud and to the low rotational speed of the centrifuge.

Table 6.4 - Properties of Formulations C and C'

Mud Property	Formulation C' Mud	Formulation C' Effluent Mud	Formulation C' Remixed Mud	Formulation C Mud
Density, ppg	9.4	8.7	9.3	9.6
PV, cp	20	17	19	22
YP, lbf/100 sq ft	10	11	11	10
6-rpm reading	7	7	7	7
10 sec. Gel Str.	7	7	7	7
10 min.. Gel Str.	9	9	9	9
ES, volts	660	934	721	474

The tests on this mud were run at an average of 650 rpm with a residence time of approximately 171 seconds. Rotational speed at the lower end of the previously tested range was selected because the density of the low density effluent was found to be relatively insensitive to the rpm. In an attempt to compare lab centrifuge performance to that of larger centrifuges, the value of g-force multiplied by residence time, g x t, was compared between devices. The maximum calculated g x t value from this speed setting is approximately 1.1×10^5 ft/sec. This resulted in a g x t value significantly lower, as shown in Figure 6.1, than the estimated g x t range of 1.6×10^6 ft/sec to 3.6×10^6 ft/sec for the oilfield centrifuge. It was discovered after the testing that the internal volume of the field centrifuge had been incorrectly calculated. Unless more exact volumes and residences times for a field centrifuge are known, g x t may not be the most accurate method to relate field centrifuges and laboratory centrifuges.

Formulation C' had much better emulsion stability than Formulation C. As in the previous series, the emulsion stability of effluent was enhanced during the centrifuge testing, as shown in Table 6.4. Although the synthetic fluid to water ratio of the effluent was not measured, the higher emulsion stability tends to indicate that centrifuge separation forced some of the water to partition from the effluent into the heavier basket slurry. This reasoning is supported by the observation from Table 6.4 that the remix mud, obtained by mixing the centrifuge effluent and basket-slurry together had lower emulsion stability than the effluent.

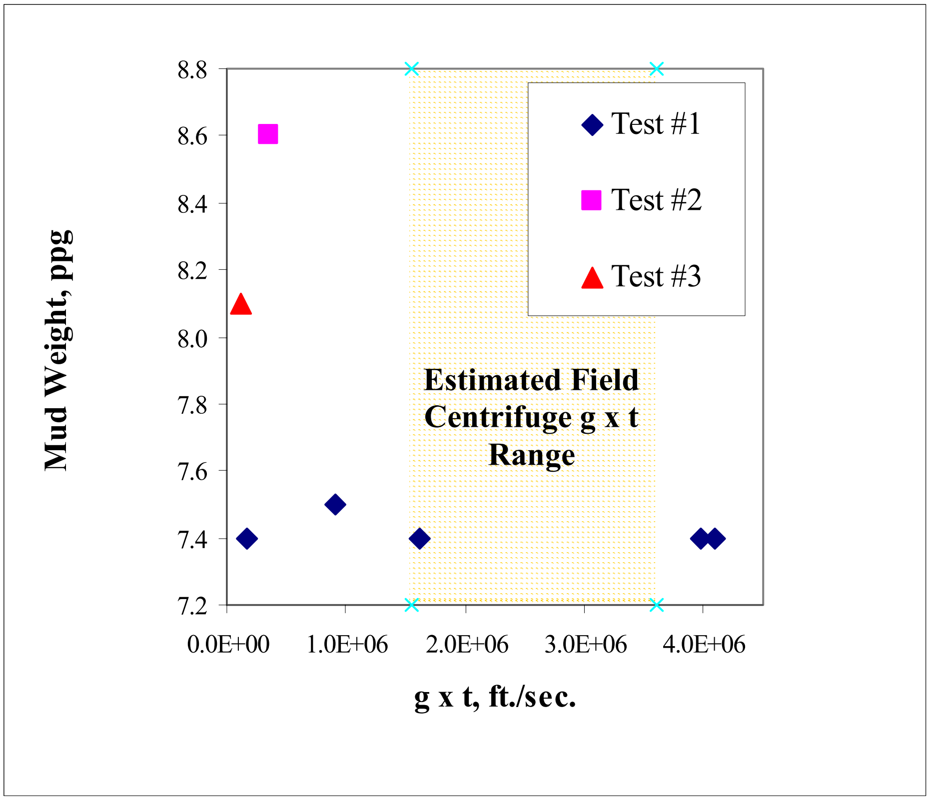

Figure 6.1 - Effluent Mud Weight versus the Product of g-Force and Residence Time (g x t) in Basket Centrifuge for all Three Sets of Tests.

6.1.3 Basket Centrifuge Separation of Original Riser Mud at Constant Speed - Test #3

There were concerns regarding the previous two tests that the results were affected by their transient nature. The fluid samples from Test #1 were affected by the variety of different speeds used during the test. In both tests, the rotating bowl was empty when the test began and filled during the test. In an attempt to overcome these transient effects in Test #3, the bowl of the centrifuge was filled with mud (¾ gallon) before starting the test. The mud for this test run, the effluent, and the final remixed mud had properties as shown in Table 6.5. This test was conducted at approximately 570 rpm. The average flow rate during this test was 0.75 gallons per minute. This test used a mud obtained by mixing the light effluent and heavier basket slurry from the first test run to give a density of 9.3 ppg. The density of the remixed fluid was lower than that of the initial formulation due to loss of barite in process of recovering materials from the centrifuge. The reverse happened through Test #3 as the remixed mud measured 0.1 ppg greater than the initial test mud. This is due to the mud products having to be removed by hand from the centrifuge basket. The approximate residence time for this test was 73 seconds. The g x t product was roughly equivalent to that in the first set of conditions used in Test #1.

Table 6.5 - Measurements from Test #3

Mud Property	Initial Test Mud	Effluent Mud	Remixed Mud
Density, ppg	9.3	8.2	9.4
PV, cp	16	10	13
YP, lbf/100 sq ft	4	6	4
6-rpm reading	3	3	2
10 sec. Gel Str.	3	3	3
10 min. Gel Str.	4	4	4
ES, volts	359	318	339

The Formulation A' mud used in this test was not treated with viscosifier as in Test #2. It was observed that there was no marked improvement in emulsion stability as with earlier tests. It is important to note that the density of the effluent was 8.2 ppg compared to 7.4 ppg in the first test with the same mud. This confirms that prefilling the centrifuge heavily influenced the separation efficiency. This phenomenon was not studied further. It is also important to note that the density of the effluent in this test was still lower than for the viscosified mud, confirming the effect of viscosity on separation efficiency.

6.1.4 Basket Centrifuge Testing Summary

The density contrast between the two separated constituents of the feed mud, the basket slurry and the effluent fluid, make them comparable to the needed wellbore and dilution muds in a riser dilution system. From Test #1, the basket slurry is 16.2 ppg, which is roughly that desired for a wellbore mud, and the effluent fluid, at 7.4 ppg, is a suitable density for a dilution mud. However, the PV and YP of the basket slurry are twice the desired values and therefore unusable. The basket slurry emulsion stability also shows possible signs of unequal distribution of the internal water phase after separation. The YP, 6-rpm reading, and gel strengths for the remixed riser mud are substantially less than the desired values. Therefore, although centrifuge separation of mud Formulation A' gives densities suitable for a riser dilution system, the rheologies do not meet the desired mud specifications. These results also show a greater density contrast between wellbore and dilution mud than achieved by de Boer, but less favorable PV and YP compared to de Boer's results.

The viscosity of the test mud appears to be an important factor controlling the density of the effluent fluid obtainable from centrifuge separation as observed from a comparison of Test #1 and Test # 2. The rotational speed and residence time of the centrifuge are also important as seen from a comparison of mud property observations from Test #1 with those of Tests # 2 and #3. An ideal riser mud would have low shear rate rheology somewhat greater than that of the Formulation C' mud used in Test # 2 therefore it would need to be subjected to a greater amount of centrifugal force and/or residence time to reduce the effluent fluid density down to what was observed in Test # 1. However, the rheology of the bowl slurry, representing a wellbore mud, would probably been even higher and was already too high to measure.

Due to incorrect calculations of the internal volume for fluid and residence time, only the 1850 rpm test run from Test #1 achieved a g x t value that was in the estimated range of g x t values for a field centrifuge. This limits the relevance of comparing mud property results to those of de Boer or for predicting expected field performance.

6.2 Hydrocyclone Testing

The objective of hydrocyclone testing was to determine whether and how hydrocyclones may be used in a separation system for a riser dilution, dual density drilling system. This is important because hydrocyclones were not being examined by de Boer or others and might provide a simpler, more compact separation system. Tests were performed on the riser mud based on Formulation A because it had the best properties in the previous testing.

6.2.1 2" Clay Ejector Hydrocyclone Testing

The first hydrocyclone tested was a 2" clay ejector recommended by M.I. Swaco. The mud was an initially unweighted version of Formulation A with a density of 7.5 ppg. Later during the testing, it was weighted up to 8.5 ppg, and finally, to 9.5 ppg. 9.5 ppg was the density of interest for this testing as it corresponds to the ideal riser mud density as described in Section 3.3.

Testing with the 7.5 ppg mud was preparatory and done to provide an initial indication of how this hydrocyclone would perform. Single pass flow split and flow split tests initiated from steady state conditions were carried out to determine the effect of feed pressure on the throughput and flow split. These results are shown in Appendix A, Tables A.1 and A.2. The head pressure was varied from 18 to 45 psig to see how this would affect performance. Steady state testing was not extensively pursued with the unweighted mud as the density contrast was so small that it was almost unnoticeable. The underflow /total flow ratio, referred to as "flow ratio" by Bradley[32], exhibited contradictory behavior between the two sets of the tests. This variation was small and was not examined further. The flow ratio from these tests ranged from 0.30 to 0.35.

The mud was weighted to 8.5 ppg, and testing was resumed by performing flow split tests initiated from steady state flow conditions at head pressures of 38 and 50 psig. The flow ratio varied from 0.30 to 0.33 in these tests. The results of these tests are shown in Appendix A, Table A.3. The feed SBM density in these tests was greater than 8.5 ppg due to the adjustment of the mud return lines from the UF and OF tanks returning slightly more UF mud than needed relative to the returning OF mud. A density sample taken from the feed tank during operations at 50 psig head pressure and 30.0 gpm to the hydrocyclone measured 8.7 ppg. The measured flow ratios from these tests correspond closely to flow ratios calculated using a material balance based on UF and OF densities shown in Table 6.6. Equation 6.1 was used to make these material balance calculations. This correspondence implies that the observed flow ratios of 0.30 to 0.34 are representative of the true flow ratio.

Table 6.6 - Flow Splits Calculated from Mass Balance

Pressure, psig	Feed Mud, ppg	OF Mud, ppg	UF Mud, ppg	Flow Ratio
50	8.7	7.85	10.35	0.34
38	8.6	7.85	10.3	0.31

$$\frac{Underflow \quad volumetric \quad rate}{Total \quad volumetric \quad rate} = \left(\frac{\rho_{FEED} - \rho_{OVERFLOW}}{\rho_{UNDERFLOW} - \rho_{OVERFLOW}} \right) \qquad (6.1)$$

Recirculation of OF and UF streams using 2” clay ejector with 8.5 ppg mud was performed next as described in Section 5.3.1 on page 44. Recirculation testing of the OF stream was performed first. This testing showed the density of the feed stream reduced from about 8.7 ppg to about 8.0 ppg converging therefore towards 7.9 ppg as the barite was removed. The detailed results from three OF recirculation tests are shown in Appendix A, Table A.4. Tests with all of the OF stream being recirculated were done to give an estimate of the maximum possible reduction in density of an OF stream if recirculation is used. These results imply that significant reprocessing of hydrocyclone OF from an 8.8 ppg initial feed density is likely to only reduce the final OF density to about 7.8 ppg.

Reprocessing of the UF stream was performed to determine how dense the UF mud could be made by concentrating the UF stream. Results for three tests, in Appendix A, Table A.5, show that the densities of the UF stream increase over time to approach about 11.4 ppg. Since about 70% of the total flow goes into the OF tank, it fills up faster than the UF tank did in the previous tests. Filling up of the OF tank limits the time duration for which UF recirculation can be continued. In these cases, the practical test duration was too short to allow the entire volume of the feed tank to be processed. Nevertheless, as more low density fluid was trapped in the OF tank, the barite was concentrated in the feed tank by the flow stream from the UF tank. These results imply that continuous reprocessing of hydrocyclone UF from an 8.8 ppg initial feed density is likely to increase the final UF density to at least 11.4 ppg. As the test duration was limited, the density should increase to a greater value in a longer test with a lower effective processing rate.

The 2" clay ejector hydrocyclone was next tested with 9.5 ppg mud. This group of tests was intended to be the most relevant as the original feed mud density of 9.5 ppg is the expected density of the returning riser mud in a practical dual density drilling system. This is also very close to the 9.3 ppg riser mud density achieved in de Boer's Test #2 with OBM. To prepare for the tests, a 100 lb sack of barite was added to the 8.5 ppg mud to increase the density to 9.5 ppg. However, the feed density during the steady state flow testing was measured at 9.9 ppg. This higher density is due to the adjustment of the mud return lines from the UF and OF tanks returning slightly more UF mud than needed relative to the returning OF mud. The testing performed here was similar to the testing done with the mud at 7.5 ppg and 8.5 ppg. The steady state and flow split tests were followed by OF and UF recirculation tests, respectively.

Results for steady state performance representing single pass hydrocyclone separation of 9.9 ppg feed fluid are listed in Table 6.7 and show flow ratios from 0.27 to 0.30. The flow ratios using mass balance were 0.28 and 0.31. Again, these results and calculations show that the true flow ratio, for the system conditions, is about 0.30. The separated OF and UF fluid streams were fed back to the feed tank and remixed in that tank to be pumped back to the hydrocyclone. This testing method allowed relatively long tests that achieved reasonably steady state conditions. The average volumetric flow rate was 35.6 gpm.

Table 6.7 - Steady State Flow Testing of 9.9 ppg Feed Mud

Flow Test Run	OF start, gal.	OF finish, gal.	UF start, gal.	UF finish, gal.	Time, sec.	Flow Rate, gpm	Flow Ratio	Pressure, psig
1	14.0	30.0	2.0	8.0	34	38.8	0.27	56
2	14.0	30.0	3.0	10.0	40	34.5	0.30	56
3	15.0	30.0	3.0	9.0	38	33.2	0.29	56
4	15.0	30.0	2.5	8.5	35	36.0	0.29	58
Mud Samples	Feed Mud, ppg		OF Mud, ppg		UF Mud, ppg		Flow Ratio	Pressure, psig
Start	9.9		8.55		12.85		0.31	56
Finish	9.8		8.4		13.4		0.28	58

These steady state separation tests represent the expected density of the OF and UF fluid streams when a 9.9 ppg riser mud makes a single pass through the 2" clay ejector hydrocyclone. The density of the inlet fluid stream was reduced by 1.3 ppg to 1.4 ppg in the OF stream, whereas the density was increased by 3.0 ppg to 3.6 ppg for the UF stream. The start and finish UF density values differed substantially. This is attributed to inconsistencies in flow through the system or inadequacies in the method used to measure UF density or a combination of both.

One final steady state test was performed with the 2” clay ejector hydrocyclone. For this test the UF and OF tank drain lines were positioned to return fluid streams in such proportions to the feed tank so that the feed mud density was 9.5 ppg. The properties of the Formulation A riser mud during this steady state processing are shown in Tables 6.8 compared to the desired values, de Boer’s results, and centrifuge Test #3 results.

Table 6.8 - Comparison of Riser Mud Properties

Mud Property	Riser Mud Equivalents			
	Desired Values	de Boer's Riser Mud	Centrifuge Test Remixed Mud	Hydrocyclone Feed Mud
Density, ppg	9.5	9.3	9.4	9.5
PV, cp	15 - 25	32	13	15
YP, lbf/100 sq ft	15 - 25	12	4	14
6-rpm reading	8+	NS	2	7
10 sec. gel	8+	NS	3	8
10 min. gel	15+	NS	4	10
ES, volts	>400	NS	339	1648

The hydrocyclone feed mud properties meet or are very close for all desired properties except for the 10 minute gel strength, which is somewhat lower than desired. The hydrocyclone feed mud YP value is slightly greater than that of de Boer’s and the feed mud PV is slightly less than half of de Boer’s PV. The YP and ES are 3 to 4 times greater for the hydrocyclone feed mud compared to the remixed mud from the centrifuge test, and the 6-rpm, 10 second and 10 minute gel strength readings are greater by more than a factor of two. This comparison between the hydrocyclone feed mud and centrifuge remixed mud results suggests that the shear and heating from the hydrocyclone processing enhances the mud properties. The rheology and emulsion stability measurements for the feed, UF, and OF from this steady state test are shown in Table A.6.

The measured UF mud density of this steady state hydrocyclone test was 11.5 ppg, which was 0.7 ppg less than the predicted value, the prediction method of which will be presented in Section 6.2.2. This lesser value of UF density is attributed to an increase of the UF outlet diameter due to erosion and also due to inaccurate measurement of the UF density, which was encountered and subsequently diagnosed in later testing.

Recirculation of OF and UF streams as performed with the 8.5 ppg mud was performed using the 9.5 ppg Mud. The first test here involved recirculation of the OF stream as was done earlier using the 8.5 ppg mud. This was done in order to understand the limits of the lowest density achievable by reprocessing of OF stream from a riser mud with initial feed density of approximately 10 ppg. OF recirculation test results are summarized in Table 6.9 and show the final feed and OF densities of 8.5 ppg and about 8.3 ppg, respectively, were converging. The test had to be stopped within three minutes because most of the fluid was transferred from feed tank to the UF tank. If the test could be continued for longer duration, the logical extrapolation would be convergence of feed and overflow stream density at about 8.3 ppg, after most of the barite from the fluid stream is removed by the hydrocyclone processing.

Recirculation of the UF stream was done to explore the highest density achievable by reprocessing of UF stream from a riser mud with an initial feed density of approximately 10 ppg. The test had to be stopped once the OF tank was filled. With approximately 70 % of the flow diverted to OF tank, it filled up in less than 1 minute, limiting the duration of the test. Nevertheless, the test results listed in Table 6.10 showed an increase in density in both for the feed and the UF streams.

Table 6.9 - Recirculation of OF Stream of Mud with Initial Feed Density of 10.0 ppg

Property	Test #1	Test #2	Test #3
Pressure, psig	58	58	56
Feed Density, start, ppg	10.1	10.0	10.1
Overflow Density, start, ppg	8.6	8.6	8.6
Feed Density, finish, ppg	8.6	8.6	8.4
Overflow Density, finish, ppg	8.3	8.3	8.3
Time, Seconds	122	161	149
Underflow level, start, gal.	4.5	4	7
Underflow level, finish, gal.	25	30	30

Table 6.10 - Recirculation of UF stream of Mud with Initial Feed Density of 10.1 ppg

Property	Test #1	Test #2	Test #3
Pressure, psig	58	58	59
Feed Density, start, ppg	10.1	10.2	10.1
Underflow Density, start, ppg	13.7	14.4	13.7
Feed Density, finish, ppg	10.9	10.8	10.7
Underflow Density, finish, ppg	14.7	14.6	14.1
Time, Seconds	58	53	55
Overflow level, start, gal.	13	13	15
Overflow level, finish, gal.	35	35	35

At the beginning of the test, the UF density was 13.7 ppg or 3.6 ppg more than the feed density. By the time the test was terminated, the density of UF stream had risen to about 14.7 ppg due to the concentration of solids in the feed flow stream. This concentration of solids was due to the continuous trapping of the OF fluid stream during the test. It is likely that the UF density could rise to a higher value for a longer test representing additional reprocessing.

6.2.2 2" Clay Ejector Testing Performance Predictions

Predictive equations for UF and OF densities of the 2" clay ejector hydrocyclone were generated using regression analysis based on the independent variable of feed density. These equations were useful for predicting the performance of the hydrocyclone for varying feed density and were generated in Microsoft© Excel.

The regressions for UF density and the OF density were based on 7 experimental observations of feed density and the associated UF density and OF density. These regressions are shown graphically in Figure 6.2. The predictive equations are as follows:

$$UF \quad Density = 2.3499 \times Feed \;\; Density - 10.132 \tag{6.2}$$

The UF regression has a correlation coefficient of 0.972.

and

$$OF \quad Density = 0.4736 \times Feed \;\; Density + 3.7974 \tag{6.3}$$

The OF regression has a correlation coefficient of 0.950.

The flow ratio for the 2” clay ejector hydrocyclone was determined from the average of 25 flow split experiments. The change in volume of the underflow and overflow tanks was recorded over time to determine the flow ratio. The flow ratio determined this way is 0.32. The OF rate/ total flow rate then is 1 - 0.32 = 0.68. The raw data for equations 6.2, 6.3, and the flow ratio are shown in Appendix A, Tables A.7, A.8, and A.9.

6.2.3 2” Adjustable Hydrocyclone Testing

A different, more conventional 2” hydrocyclone was tested to assess its performance and determine if it could be part of a practical separation system in a riser dilution, dual density drilling process.

Steady state and flow split tests, as previously described, were conducted with this hydrocyclone. The results are in Appendix B, Tables B.1 and B.2. This hydrocyclone was tested first with the UF tip removed. It gave less density contrast between feed density and UF density and a larger UF split than the clay ejector hydrocyclone. Performance with the UF tip removed was not useful, and further testing was conducted with the tip installed.

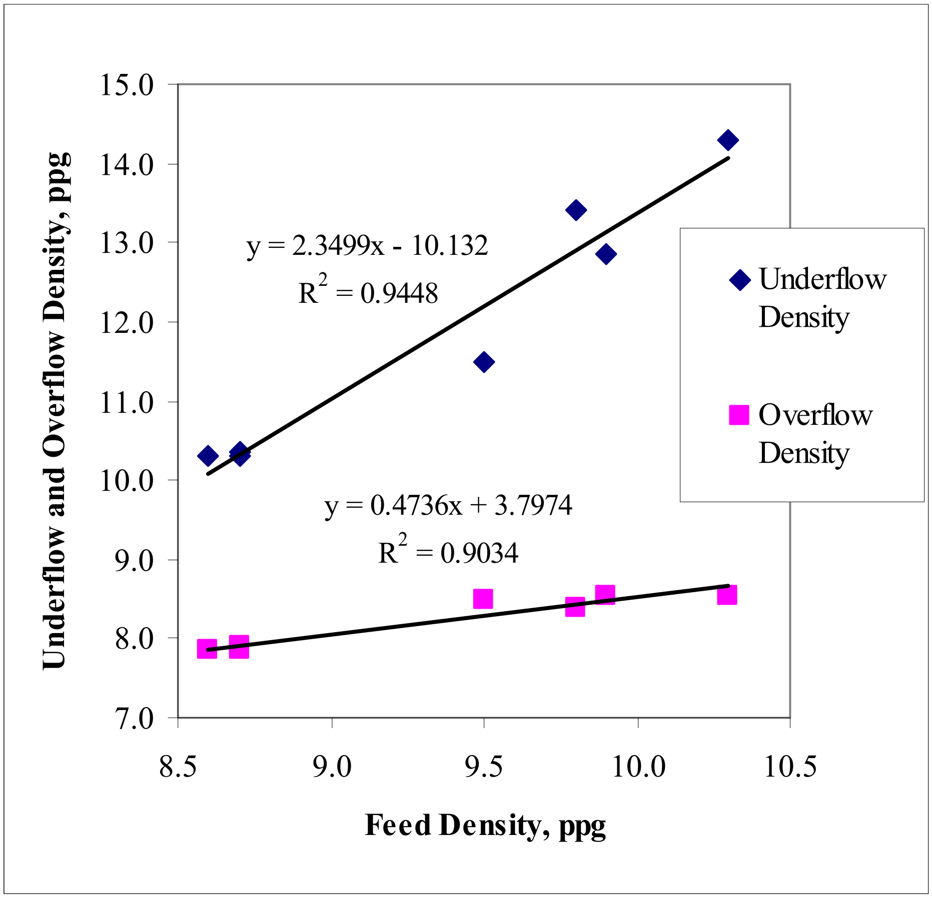

Figure 6.2 - Measured Underflow and Overflow Density versus Feed Density for The 2” Clay Ejector Hydrocyclone

The 2” adjustable hydrocyclone was next tested with various tip sizes. Flow split and steady state testing were performed using the standard 0.19” UF tip supplied with the hydrocyclone. The flow ratios, shown in Table 6.11, with this tip were very small, averaging 0.076. This tip size proved useful in two stage testing later.

Table 6.11 - Flow Splits with 0.19” UF Tip

Test Run	OF Lvl., gal.	UF Lvl., gal.	Q, gpm	Time, sec.	Flow Ratio	Head Pressure, psig
1	35	3	29.6	77	0.079	58
2	37	3	30.8	78	0.075	59
3	36.5	3	29.6	80	0.076	59
4	37	3	30.0	80	0.075	60

The density contrast between the UF and OF mud streams was very large, as can be seen in Table 6.12. The calculated flow ratios using mass balance did not match as well with the measured flow splits as was the case in earlier hydrocyclone testing. This difference in values is attributed to the inability to determine UF density precisely. This problem became more prominent later in the testing and will be further addressed in Section 6.3.1.

Table 6.12 - Steady State Densities and Estimated Flow Splits for 0.19” UF Tip

Feed Mud, ppg	UF Mud, ppg	OF Mud, ppg	Head Press, psig	Flow Ratio
10.0	18.9	9.1	58	0.092
9.7	17.4	9.0	58	0.083
10.0	17.7	9.2	58	0.094

The standard hydrocyclone tips were cut to provide 0.27” and 0.37”openings. The 2” adjustable hydrocyclone was tested using these two tip sizes with the 0.37” being tested most heavily. Results from these tests, shown in Appendix B, Tables B.3 and B.4, were used along with results for the 2” adjustable hydrocyclone with the UF tip removed and with the 0.19” UF tip to determine how tip size controlled UF density/feed density and flow ratio. Trend line equations for both factors were used to aid in choosing hydrocyclone combinations for the two stage processing of the first stage UF stream. At the time, this appeared to be the best alternative; however, this was not the case as will be shown.

6.3 Two Stage Hydrocyclone Processing

Evaluation of two stage processing was carried out initially by processing of the first stage UF stream and subsequently using processing of the first stage OF stream. The purpose for all of these experiments was to determine if any of these two stage hydrocyclone combinations could perform the necessary separation resulting in a useable wellbore mud and dilution mud and justify further testing.

6.3.1 Two Stage Processing of the 1st Stage UF Stream

Two distinct pairings of hydrocyclones were chosen based on the trend line equations discussed at the end of Section 6.2.3. The first test used the 2" adjustable hydrocyclone with the 0.44" UF tip for the first pass and the 0.63" UF tip for the second pass. The UF and OF tank levels, time of flow, head pressure, and density of feed, UF and OF flow streams were all measured in most tests with a few exceptions. The results from the first and second stages of the first set of tests performed are presented in Tables 6.13 and 6.14.

Table 6.13 - Results from 1st Stage of 1st Test Using 0.44" UF Tip

Feed Density, ppg	UF Density, ppg	OF Density, ppg	Head Pressure, psig	Mass Balance Flow Ratio	UF Lvl., gal.	OF Lvl., gal.	Tank Level Flow Ratio
9.5	11.1	8.4	55	0.26	26	56	0.32

Table 6.14 - Results of 2nd Stage of 1st Test Using 0.63" Tip

Feed Density, ppg	UF Density, ppg	OF Density, ppg	Head Pressure, psig	Mass Balance Flow Ratio	UF Lvl., gal.	OF Lvl., gal.	Tank Level Flow Ratio
11.2	13.85	8.7	65	0.49	16	13	0.55
11.2	12.95	9.3	NT	0.52	16	10.5	0.60
11.25	13.7	9.1	55	0.47	16	11	0.59
11.3	13.8	8.7	60	0.51	14	11	0.56
11.25	13.8	8.65	60	0.50	15	11	0.58
11.2	13.8	8.6	60	0.50	15	11	0.58

There is a marked difference between the flow ratio determined from tank levels and the flow ratio calculated from mass balance for both stages of the first test set. Taking into consideration that flow ratio measured from tank levels is a direct reading, this brings the value of flow ratio from mass balance into question since this mass balance is based on density measurements, which were, especially for the UF, questionable. This problem is addressed further in Section 6.3.4.

The second set of tests used the 2” clay ejector hydrocyclone for the first stage and the 2” adjustable hydrocyclone with a 0.63” UF tip for the second stage. The results from the first and second stages of the second set of tests performed are presented in Tables 6.15 and 6.16. Again, there was notable disparity between the flow ratio measured from tank level change and that calculated from mass balance. This disparity is attributed to the same reasons as given for the first two stage test described above.

Table 6.15 - Results from 1st Stage of 2nd Test Using 2” C.E. Hydrocyclone

Feed Density, ppg	UF Mud, ppg	OF Mud, ppg	Head Pressure, psig	Mass Balance Flow Ratio	UF Lvl., gal.	OF Lvl., gal.	Tank Level Flow Ratio
9.4	11.85	8.5	57	0.27	24	55	0.30

Table 6.16 - Results of 2nd Stage of 2nd Test Using 0.63” UF Tip

Feed Density, ppg	UF Density, ppg	OF Density, ppg	Head Pressure, psig	Mass Balance Flow Ratio	UF Lvl., gal.	OF Lvl., gal.	Tank Level Flow Ratio
11.4	13.95	8.65	60	0.52	13	11	0.54
11.25	13.8	8.7	62	0.50	13	11	0.54
11.2	13.8	8.7	62	0.49	13	10.5	0.55

The first test gave results from the use of the 2" adjustable hydrocyclone with the 0.44" UF tip for the first stage and the 0.63" UF tip for the second stage that demonstrated a reasonable degree of separation. OF densities of 8.4 ppg from the first stage and 8.7 ppg from the second stage, would give a dilution fluid density of 8.45 ppg. The second stage UF gives a 13.8 ppg wellbore fluid stream at 18.6 % of total system flow. Results using the 2" clay ejector for the first stage were not as good in terms of density contrast.

6.3.2 Intermediate Testing Using Various Tip Sizes

After examining the results from the first two sets of two stage testing it was determined that use of the trend line equations described in Section 6.2.3 to choose hydrocyclone pairings was inadequate. The use of a multi-regression equation for UF density predictions based on recorded values of UF density, feed density, and UF outlet diameter was chosen as a better alternative along with a polynomial equation to predict flow ratio based on recorded tank level results from the testing of UF outlet tip sizes from 0.19" to 0.37". The results, shown in Appendix B, Table B.5, from testing of 0.22", 0.255" and 0.274" were used to shore up these two methods of prediction. The difference between measured and calculated flow ratio was less than in previous tests. In light of the inconsistencies cited in 6.3.1, this was fortunate and lended credibility to the flow ratio equation. Nevertheless, the volumetric flow ratio was concluded to be more likely to be accurate and was used as a basis for the following correlation. The accurate measure of density was still questionable as discussed previously. The multi-regression equation for predicting UF density and the polynomial equation to predict flow ratio were used to select the hydrocyclone pairing for the remainder of the hydrocyclone testing. The UF prediction equation is based on feed density and UF tip diameter as independent variables and UF density as the dependent variable. This equation is as follows.

$$UF\ Density = -4.122 + (2.894 \times Feed\ Density) - (27.165 \times UF\ Outlet\ Diameter) \quad (6.4)$$

The correlation coefficient for this equation is 0.908. This equation was fairly accurate at predicting the first stage density for the final test with a predicted value of 15.9 ppg and a measured value of 16.15 ppg as reported in Section 6.3.4. The equation gave very poor results for the second stage predicting approximately 5.3 ppg higher than the measured 10.35 ppg. This is attributed to this equation being based on the original barite particle size distribution in the mud prior to processing through a hydrocyclone. For the two stage test, the barite particle size distribution entering the hydrocyclone for the second stage processing is different than that entering in the first stage.

The predictive equation for the flow ratio, based on volumetric flow measurements, as a function of UF outlet diameter has a correlation coefficient of 0.994. That equation, Equation 6.5, is shown below.

$$Flow\ \ Ratio = (3.046 \times UF\ \ Dia^2) - (0.836 \times UF\ \ Dia) + 0.118 \tag{6.5}$$

UF Dia is the UF diameter in inches. In the final two stage test, in Section 6.3.4, this equation also worked best for the first stage prediction. The predicted value was 0.118 and the value calculated by mass balance was 0.119. The second stage prediction was 0.069 and the value calculated by mass balance was 0.054. A plot of flow ratio versus UF outlet diameter is shown in Figure 6.3, and the data for the two prediction methods discussed in this section are given in Appendix B, Tables B.6 and B.7.

6.3.3 Two Stage Processing of the 1st Stage OF Stream – First Phase

The hydrocyclone pairing used here was based on the predictive equations discussed in Section 6.3.2. This test involved the use of the 2” adjustable hydrocyclone with a 0.274” UF tip for the first stage with the OF fluid stream processed through the second stage with a 0.19” tip. This test was carried out as described in Section 5.6 and the results are shown in Table 6.17. The mass balance flow ratio from the first stage was consistent with the predicted value from the flow ratio regression equation described in Section 6.3.2. The inconsistent underflow densities for the second stage testing resulted in the flow ratios based on a mass balance being very inconsistent. A remedy was sought for this problem as will be described below.

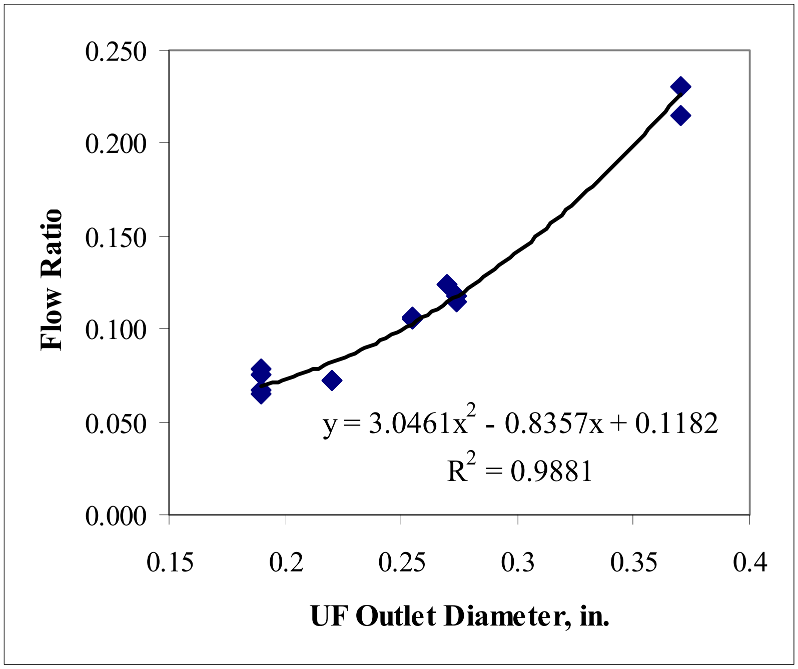

Figure 6.3 - Flow Ratio versus UF Outlet Diameter for 2” Adjustable Hydrocyclone

Table 6.17 - First Phase of OF Stream Processing

Stage	Tip size, in.	Feed Mud, ppg	UF Mud, ppg	OF Mud, ppg	Mass Balance Flow Ratio
First	0.274	9.5	16.7	8.55	0.117
Second	0.19	8.6	10.35	8.45	0.079
Second	0.19	8.55	10.1	8.4	0.088
Second	0.19	8.55	10.0	8.4	0.094
Second	0.19	8.55	10.8	8.45	0.043
Second	0.19	8.55	10.85	8.4	0.061
Second	0.19	8.5	10.8	8.4	0.042
Second	0.19	8.5	10.75	8.4	0.043

The accuracy of UF density measurements in these tests was questionable. An additional test and more sampling were performed to better diagnose this problem. The OF and UF muds from the second stage were mixed together, pumped through the second stage hydrocyclone and captured in the UF and OF tanks. Next, the UF and OF tanks were individually drained to sequentially lower levels and the mud density from the bottom of the tank was measured at each level. Lastly, multiple samples of the last gallon from the UF tank were taken. These results are shown in Table 6.18 and were taken from static conditions with no mixing of fluid volumes after the pump was stopped.

Table 6.18 - Density Measurements on Static Conditions

OF Tank Lvl., gal.	Mud Density, ppg	UF Tank Lvl., gal.	Mud Density, ppg	Final Gallon	Mud Density, ppg
43.5	8.45	3	10.75	1 sample	9.9
30	8.5	2	10.4	2 sample	9.9
18	8.45	1	10.05	3 sample	9.9
5	8.45			4 sample	9.95
				5 sample	10.0

In view of the wide range of densities recovered from the UF tank, the entire volume of mud in the UF tank was captured and thoroughly stirred before measuring the UF density for the final test. This approach was validated as described in Section 6.3.4.

6.3.4 Two Stage Processing of the 1st Stage OF Stream – Second Phase

The final two stage test was carried out in steady state as described in Section 5.7. The results are shown in Table 6.19. The tip sizes used were the same as those used in the first phase of testing described in Section 6.3.3. The problem with UF density measurement was dealt with as discussed in the previous paragraph.

Table 6.19 - Results from 2nd Phase of OF Stream Processing

Stage	Tip Size, in.	Feed Density, ppg	UF Density, ppg	OF Density, ppg	Mass Balance Flow Ratio
First	0.274	9.5	16.15	8.6	0.119
Second	0.19	8.6	10.35	8.5	0.054

Samples were taken of the feed, UF and OF mud streams of both stages during this test and the mud properties are shown in Table 6.20. The UF densities were measured by capturing the entire UF tank volume, thoroughly agitating it, taking a measurement from the top of the bucket, and at two subsequent levels after draining approximately 1 ½ gallons. The readings for the UF density of each stage were consistently the same throughout, thus validating this approach. Along with these samples, a sample representing a wellbore mud was created by mixing the UF mud from both stages in proportions that would occur if the UF from the two stages were combined as in an actual two stage set up. It was calculated that the UF mud stream from the first stage UF was equivalent to approximately 12% of total system mud flow and that the UF mud from the second stage was equal to approximately 5% of total system mud flow. Using these two percentages, 390 ml of 16.15 ppg mud and 160 ml 10.35 ppg mud were combined. The density of this mixture was 14.55 ppg. Based on the calculated flow ratios, a system set up as this would only give a wellbore mud flow rate of 16.7% of total mud flow at 14.5 ppg. The hypothetical two stage separation scheme simulated by this testing and the measured densities and flow fractions from these tests are shown in Figure 6.4.

Table 6.20 - Mud Properties from Final Two Stage Test

Mud Property	Wellbore Mud			Riser Mud		
	Desired Properties	Measured Values	de Boer's OBM	Desired Properties	Measured Values	de Boer's OBM
Density, ppg	14.5	14.55	14.5	9.5	9.5	9.3
PV, cp	40 -50	33	45	15 - 25	17	32
YP, lbf/100 sq ft	15 - 25	11	20	15 - 25	10	12
6-rpm reading	15 - 25	7	NS	8+	6	NS
10 sec. Gel Str.	15 - 20	8	NS	8+	7	NS
10 min. Gel Str.	16 - 22	12	NS	15+	9	NS
ES, volts	>400	774	NS	>400	799	NS

The ideal wellbore mud flow rate is 20% for a 4 to 1 dilution ratio. Making up the other 3.3% of flow needed for the wellbore mud with the 8.5 ppg OF stream from the second stage would give a wellbore mud density of 13.5 ppg.

As a check to determine if flow splits were calculated accurately, 450 ml of 8.5 ppg and 90 ml of 14.55 ppg were mixed and resulted in a "remixed" 9.5 ppg riser mud. This confirms that calculations are consistent with measured feed, UF and OF mud densities.

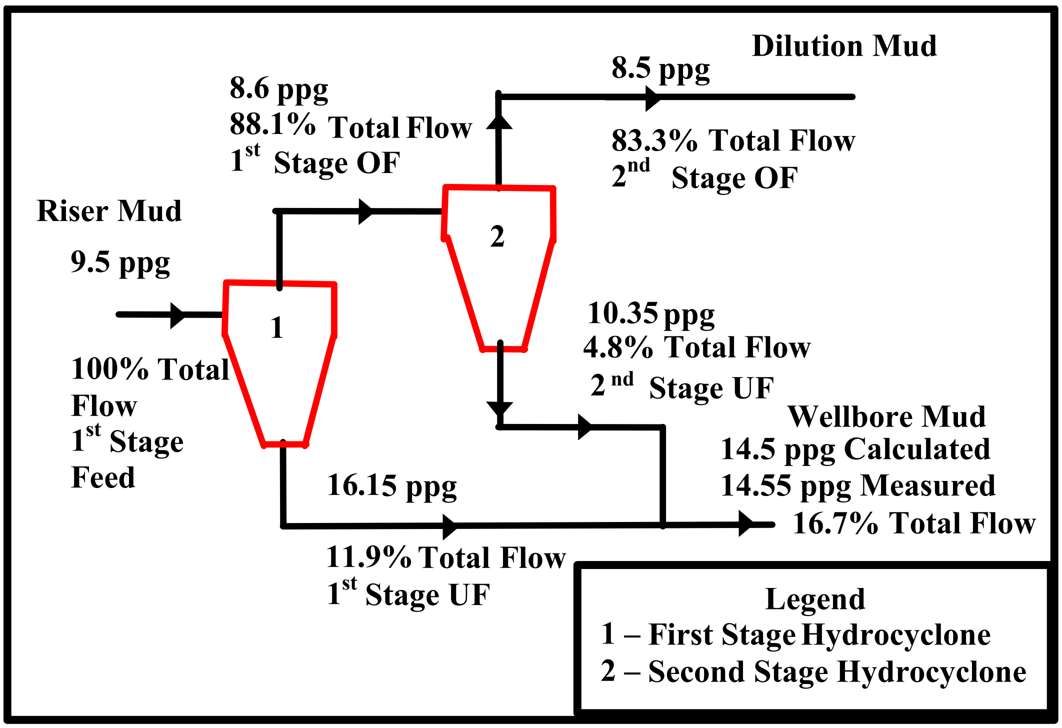

Figure 6.4 - Hypothetical Two Stage Hydrocyclone Scheme Using Results from Actual Tests

The PV and YP for the wellbore mud were lower than expected. Consequently, the PV and YP are substantially lower than the desired values and those achieved by de Boer. The 6-rpm readings and gel strengths are lower than desired as well. The YP for the riser mud is substantially lower than the desired value, and the 6-rpm reading and gel strengths are only slightly lower than the desired values. The riser mud YP is close to de Boer's and the PV is almost half of de Boer's PV value. The emulsion stabilities are very high, but are nevertheless, lower than readings from previous experiments as seen in comparison with Table 6.8. These low values can be attributed to the addition of 50 gallons of new mud to provide sufficient mud volume for the two stage testing. This new mud was not sheared and heated enough to make it yield to the extent seen in the original test mud. Also, a small amount of water was added to the mud during two stage testing to make up for evaporation losses, which contributed to the lower ES value as well.

This test most closely approximates continuous processing with a practical two stage separation system. Overall conclusions regarding hydrocyclone separation systems based on this and other tests are given in the following section.

6.4 Summary of Hydrocyclone Tests

The results using the 2” clay ejector hydrocyclone show that it provided separation, but with less contrast in discharge densities than the centrifuge. For a 9.5 ppg feed mud, the UF mud density measured 11.5 ppg. This implies that hydrocyclones would have to be used in a staged arrangement to provide the necessary wellbore mud density for a riser dilution system.

The feasibility of staged hydrocyclones giving increased separation and density contrast was confirmed by recirculation tests. Results from the OF recirculation testing with 10.0 ppg feed mud showed the systems ability to reduce mud density down to 8.3 ppg.

Hydrocyclone processing greatly improved YP, 6-rpm reading, the gel strengths and the emulsion stability compared to laboratory centrifuge and simple laboratory formulation tests. Most of these mud properties increased by a factor of two or more when comparing a 9.5 ppg riser mud from hydrocyclone steady state processing to the remixed 9.4 ppg mud from centrifuge testing. The emulsion stability at this point was typically well over 1000 volts for the hydrocyclone processed 9.5 ppg mud. This is attributed to the extensive heat and shear from the hydrocyclone testing process, which would also be expected in any system applied in the field.

The 2” adjustable hydrocyclone proved to be the most useful hydrocyclone for two stage testing. This hydrocyclone was configured in many different ways by simply changing the UF tip shown in Figure 5.10. Conversely, the 2” adjustable hydrocyclone with the UF tip removed was found to be less useful for two stage processing.

Use of multi-regression analysis based on UF tip diameter and feed density to predict UF density is a fairly accurate method to predict the first stage UF density. This analysis was not predictive of UF densities for the second stage, probably because of the different barite particle size distribution in the second stage feed.

The measurement of UF density at the drain from the UF tank proved to be problematic as shown by the frequent disparity between the flow ratios based on a mass balance and those based on volume measurements and also by the variation in UF density presented in Table 6.18. This problem was only solved by draining the entire UF tank volume into a bucket, mixing, and then taking a sample to measure density. This solution was only used during the very last two stage test described in Section 6.3.4.

The results from the two stage testing using processing of the first stage UF stream shows the possibility of achieving a wellbore fluid stream of 13.8 ppg at 18.6% of total flow. The first stage of this particular test had an OF density of 8.4 ppg, which was the lowest density seen in the two stage testing.

The results from the final two stage hydrocyclone processing experiment were comparable to de Boer’s in terms of wellbore mud density with a measured value of 14.55 ppg for the remixed wellbore mud compared to 14.5 ppg for de Boer’s. The wellbore and riser mud

YP, 6-rpm reading, and gel strength were less than desired and than achieved by de Boer. This implies hydrocyclone processing was not as effective as a centrifuge. However the low rheology values can be attributed in part to the recent addition of new mud to build volume and a recent water addition. Therefore, the results for the final two stage tests are significant considering that the hydrocyclones used were essentially off the shelf items and the initial mud properties were less than optimum. In addition, the minimum density achieved in a hydrocyclone overflow was 8.3 ppg and the maximum underflow density was over 16 ppg when processing a 9.5 ppg riser fluid. Although the flow fractions achieved at those densities do not support the desired dilution ratio, these results demonstrate that multi-stage hydrocyclone processing can achieve large density contrasts. Therefore, further improvement in mud and hydrocyclone separation performance should be possible and could give results more comparable to those achieved by de Boer.

7. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

7.1 Summary

Dual density drilling is a promising approach for accessing sources of oil and gas that have been considered inaccessible to conventional, single density drilling, especially for deepwater prospects. Riser dilution is one possible alternative for applying dual density drilling in the field. The practicality of a riser dilution approach depends on the ability of the wellbore and riser muds to suspend barite and transport cuttings. Separating the riser mud back into useable wellbore mud and dilution mud is necessary in order for such a system to operate effectively.

A synthetic-base drilling mud formulation was developed to meet specifications for representative deepwater wells, and the unweighted formulation was chosen as the dilution fluid. Target mud densities were chosen based on the most extreme case provided by industry and on dilution of the wellbore mud at a 4 to 1 dilution fluid to wellbore fluid ratio. Testing in the laboratory scale setting failed to produce a mud formulation with all of the necessary functions for barite suspension and cuttings transport in both the wellbore and riser muds.

Laboratory testing with a basket centrifuge was performed to supplement the nearly full scale testing done by de Boer. The prototype riser mud was centrifuged at a variety of g-force levels and residence times, which gave products with densities suitable for a riser dilution system. However, the resulting wellbore mud was too viscous for use. Remixing of the dilution and wellbore muds to examine a resulting riser mud showed little change in overall mud properties from the original feed mud.

Separation of the proposed riser mud formulation was then performed with various hydrocyclones. The degree of separation observed in steady state testing indicates that hydrocyclones would need to be staged for a riser dilution system. Performance testing on individual hydrocyclones was conducted and the results used to devise two stage separation schemes. The final two stage separation approach gave a degree of separation only slightly less than the current state of the art in riser dilution technology established by de Boer, in terms of densities. The resulting mud rheology was somewhat less than the desired properties, but was improved significantly versus the laboratory testing results.

7.2 Conclusions

7.2.1 Drilling Mud

1. The goal of achieving a mud formulation that would allow dilution of a 17.0 ppg weighted wellbore mud with an unweighted 7.4 ppg dilution mud and still retain the properties necessary for suspending barite and transporting cuttings was not achieved in the laboratory testing phase.
2. Separate research by de Boer indicated that more appropriate rheologies with an oil-base mud system are achievable, at least when using a 14.5 ppg wellbore mud. More appropriate rheologies were also observed in the hydrocyclone tests conducted for this study. In both cases, it appears that two effects contribute to low shear rate rheology that is better than in the laboratory study. One is that the barite fines retained after separation improve rheology of the low density phase. The other is that SBM low shear rate rheology increases with time, temperature, and shear.
3. Formulating a synthetic-based mud system that has a stable invert, water-in-oil, emulsion for all three mud streams of a dual density system is readily achievable.
4. Suitable high temperature, high pressure fluid loss results for a wellbore mud were not achieved in the final sample formulations but are not expected to be difficult to achieve.

5. The annular velocities in the riser will be significantly higher with a riser dilution system than for conventional, single density drilling operations and may reduce the importance of riser mud rheology for suspension of barite and transporting cuttings.

7.2.2 Separation

1. Centrifuge separation did give the needed mud densities for a riser dilution system. Research by de Boer confirmed that dilution and wellbore muds with reasonable, if not ideal, density and rheology could be recovered from a riser mud using a field-applicable, pilot-scale centrifuge. LSU experiments further demonstrated that centrifuges could potentially separate a riser mud into high and low density streams of almost any densities between those of the mud base fluid and the maximum desired wellbore mud. Therefore, centrifuges have an apparent advantage over hydrocyclones for meeting the density requirements of a dual density system with a minimum number of stages of separation.
2. Hydrocyclone processing does not generally give as great a density contrast between the wellbore and dilution mud streams as centrifuge separation. Hydrocyclones with smaller underflow outlet diameter sizes will give density contrasts comparable to centrifuges, but the percent of mud flow to the underflow stream is typically very small.
3. Results from the OF recirculation testing of the 2” clay ejector showed the ability of a hydrocyclone to reduce the density of the Formulation A mud to 8.3 ppg. This could prove useful if a system achieving a combination of a wellbore fluid stream of 14.3 ppg and 20% of total volumetric flow and a dilution fluid stream of 8.3 ppg and 80% of total system flow was devised that would essentially match results achieved by de Boer.
4. A major goal of this research was to demonstrate the potential feasibility of using hydrocyclones in lieu of centrifuges to perform the separation of riser mud into dilution

and wellbore muds. This goal was not achieved. However, the final two stage separation test delivered 16.8 % of total system mud flow as a 14.55 ppg wellbore mud and the remaining mud flow as an 8.5 ppg dilution mud. Also, the two stage processing of the first stage UF gave a 13.8 ppg wellbore mud at 18.6% of total volumetric flow. Therefore two stage processing did give results approaching this goal.

5. A qualitative comparison makes it clear that a hydrocyclone separation system may offer a feasible and desirable alternative to centrifuge separation system at a lower capital and operational cost. A hydrocyclone system may be able to provide similar density separations while achieving better emulsion stability. Nevertheless, an optimum hydrocyclone system has not been developed and some combination of hydrocyclones and centrifuges might prove to be optimum for a riser dilution system.
6. The effect of centrifuging on the emulsion stability of the resulting flow streams is a concern. Apparently, some amount of internal water phase may shift into the heavier sediments during separation with a centrifuge.
7. Hydrocyclone processing appears to increase the emulsion stability and the rheology of the mud. This is attributed to the increased shear and heating that the mud is subjected to based on discussion with more experienced drilling fluid researchers
8. Accurate measurement of mud densities in the hydrocyclone test system was a problem. In particular, the density of underflow mud samples varied widely and was apparently greater than the average density in the underflow tank due to settling effects in the tank. This can be overcome by capturing the entire volume to be measured, mixing it well, and then taking the measurement.

9. Predictive correlations for underflow density and flow ratio developed from the hydrocyclone test results are reasonably accurate. The correlations are useful for predicting first stage underflow density and flow ratio and therefore for selecting cone type and underflow tip size to achieve desired operating performance.

7.3 Recommendations

1. Use of a hydrocyclone-based mud separation system should be given further consideration in the development of a mud-dilution based dual gradient drilling process.
2. Further work is needed to develop a drilling mud formulation that would meet the needs of this system, particularly in improvement of the low shear rheology. Three items of immediate interest are:
    a. The use of alternative clays other than standard organophillic clay must be examined. This was recommended by synthetic-base mud experts and was not investigated in this research.
    b. Heat aging must be performed on the mud to determine what kind of rheology it would attain when subjected to pressures and temperatures that approximate actual drilling conditions.
    c. The HTHP filtrate loss for the chosen formulation must be determined. If it is still excessive, filtrate control material needs to be added to the mud formulation.
3. A detailed study of the underlying theory of hydrocyclones along with an examination of vendor's literature needs to be performed and integrated with empirical models to select the best available hydrocyclones for testing to achieve the desired system goals in terms of required densities and flow rates.

4. The use of computational fluid dynamics programs designed specifically for hydrocyclones[34] should be investigated. Concepts from hydrocyclone theory should be used in hypothesizing sizes and internal geometries to be used to achieve the necessary flow ratios and density contrasts for a riser dilution system. These geometries could then be simulated to provide an indication of:
    a. Whether other hydrocyclones currently manufactured would be more suitable for the needs of the system, or
    b. Whether hydrocyclones need to be specifically designed and manufactured for this system.
5. If further development of a hydrocyclone based system is initiated, a test apparatus must be fabricated to allow testing of continuous, multi-stage processes. The design should include the following refinements, as determined to be practical.
    a. The best way to measure densities of the underflow and overflow fluid streams from a hydrocyclone should be defined based on consultation with solids control researchers.
    b. Larger tanks to accommodate testing of larger hydrocyclones should be used. These tanks need to be sized to have a retention time of at least 2, and preferably 3 to 4, minutes for the flow stream, underflow or overflow, which they are intended to contain.
    c. Piping should be sized to handle, or return pumps must be used, to return flow of the underflow and overflow streams to the system feed tank, especially for testing of hydrocyclones of 4” and greater.

d. Drip pans need to be provided for any points in the system where samples are to be taken or where hoses may be disconnected.

e. The current drain line system from the underflow and overflow tanks to the feed tank must be improved to ensure steady, unimpeded return flow and also to prevent fluid from being trapped in these lines when the system is secured.

6. A careful technical and economic comparative analysis of hydrocyclone, centrifuge, and hybrid systems is recommended.

   a. Expectations that a hydrocyclone system is likely to be less expensive, take up less space on the rig, and be easier to maintain compared to a centrifuge system should be evaluated rigorously.

   b. Predictive correlations for the 2” clay ejector and 2” adjustable hydrocyclone should be used to predict 1st stage separation performance. A similar approach should be considered to give more general performance predictions for components in any system being evaluated.

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APPENDIX A: ADDITIONAL DATA FOR 2" CLAY EJECTOR HYDROCYCLONE

Table A.1 - Results from Single Pass Flow Testing with Unweighted Mud

Test run	Head Press, psig	Total Flow, gal.	Overflow, gal.	Underflow, gal.	Time, sec.	Flow rate, gpm	Flow Ratio
1	18	44.5	29.0	15.5	132	20.2	0.35
2	28	44.5	29.5	15.0	115	23.2	0.34
3	38	44.0	29.5	14.5	101	26.1	0.33
4	45	45.5	30.5	15.0	96	28.4	0.33
5	45	43.0	29.0	14.0	90	28.7	0.33
6	45	45.0	30.0	15.0	93	29.0	0.33

Table A.2 - Results from Flow Split Tests with Unweighted Mud

Flow Test Run	OF start, gal.	OF finish, gal.	UF start, gal.	UF finish, gal.	Time, sec.	Flow Ratio	psig	Flow Rate, gpm
1	9.5	30.0	4.0	14.0	NT	0.33	45	---
2	15.0	30.0	4.5	12.0	46	0.33	45	29.3
3	15.0	30.0	4.0	12.0	46	0.35	45	30.0
4	9.0	30.0	4.0	14.0	71	0.32	38	26.2
5	10.0	30.0	4.0	14.0	65	0.33	38	27.7
6	8.0	30.0	2.8	13.0	75	0.32	38	25.8
7	5.0	25.0	3.0	11.5	72	0.30	28	23.8
8	6.0	25.0	2.5	11.0	70	0.31	28	23.6
9	5.0	25.0	2.5	11.5	75	0.31	28	23.2

Table A.3 - Results from Flow Split Tests with Mud Weighted with 100 lb. of Barite

Flow Test Run	OF start, gal.	OF finish, gal.	UF start, gal.	UF finish, gal.	Time, sec.	Flow Ratio	psig	Flow Rate, gpm
1	15.0	30.0	5.5	12.0	43	0.30	50	30.0
2	15.0	30.0	4.0	11.0	43	0.32	50	30.7
3	15.0	30.0	5.0	12.0	42	0.32	50	31.4
4	10.0	25.0	5.0	12.0	50	0.32	38	26.4
5	10.0	25.0	4.5	11.5	49	0.32	38	26.9
6	10.0	25.0	4.5	12.0	50	0.33	38	27.0

Table A.4 - Recirculation of OF Stream of Mud with Initial Feed Density of 8.8 ppg

Property	Test #1	Test #2	Test #3
Pressure, psig	52	52	52
Feed Density, start, ppg	8.8	NT	8.7
Overflow Density, start, ppg	7.9	NT	7.8
Feed Density, finish, ppg	8.0	8.0	8.1
Overflow Density, finish, ppg	7.8	7.8	7.9
Time, Seconds	162	185	170
Underflow level, start, gal.	3	3	3.5
Underflow level, finish, gal.	29	28	27

Table A.5 - Recirculation of UF Stream of Mud with Initial Feed Density of 8.8 ppg

Property	Test #1	Test #2	Test #3
Pressure, psig	52	52	52
Feed Density, start, ppg	8.8	8.8	8.5
Underflow Density, start, ppg	10.5	10.8	10.0
Feed Density, finish, ppg	9.2	9.2	9.0
Underflow Density, finish, ppg	11.4	11.4	11.1
Time, Seconds	78	78	78
Overflow level, start, gal.	13	13	12
Overflow level, finish, gal.	38	38	34

Table A.6 - Steady State Test Mud Properties with 9.5 ppg Formulation A Feed Mud

Mud Property	Feed Mud	OF Mud	UF Mud
Density, ppg	9.5	8.5	11.5
Temp., F	101	98	96
PV, cp	15	13	20
YP, lbf/100 sq ft	14	11	15
6-rpm reading	7	7	7
10 sec. gel	8	8	9
10 min. gel	10	10	13
ES, volts	1648	1545	1583

Table A.7 - Mud Density Measurements Used for Regression Equations

Feed Density, ppg	UF Density, ppg	OF Density, ppg
8.7	10.35	7.85
8.6	10.3	7.85
8.7	10.3	7.9
9.9	12.85	8.55
9.8	13.4	8.4
10.3	14.3	8.55
9.5	11.5	8.5

Table A.8 - UF and OF Tank Measurements for Flow Split Tests

Test Date	OF, gal.	UF, gal.	Flow Ratio
30-Aug-04	29.0	15.5	0.35
30-Aug-04	29.5	15.0	0.34
30-Aug-04	29.5	14.5	0.33
30-Aug-04	30.5	15.0	0.33
30-Aug-04	29.0	14.0	0.33
30-Aug-04	30.0	15.0	0.33

Table A.9 - Tank Measurements for Flow Split Tests Initiated from Steady State

Test Date	OF start	OF finish	UF start	UF finish	Flow Ratio
30-Aug-04	9.5	30.0	4.0	14.0	0.33
30-Aug-04	15.0	30.0	4.5	12.0	0.33
30-Aug-04	15.0	30.0	4.0	12.0	0.35
30-Aug-04	9.0	30.0	4.0	14.0	0.32
30-Aug-04	10.0	30.0	4.0	14.0	0.33
30-Aug-04	8.0	30.0	2.8	13.0	0.32
30-Aug-04	5.0	25.0	3.0	11.5	0.30
30-Aug-04	6.0	25.0	2.5	11.0	0.31
30-Aug-04	5.0	25.0	2.5	11.5	0.31
2-Sep-04	15.0	30.0	5.5	12.0	0.30
2-Sep-04	15.0	30.0	4.0	11.0	0.32
2-Sep-04	15.0	30.0	5.0	12.0	0.32
2-Sep-04	10	25	5	12	0.32
2-Sep-04	10	25	4.5	11.5	0.32
2-Sep-04	10	25	4.5	12	0.33
17-Sep-04	14	30	2	8	0.27
17-Sep-04	14	30	3	10	0.30
17-Sep-04	15	30	3	9	0.29
17-Sep-04	15	30	2.5	8.5	0.29

APPENDIX B: ADDITIONAL DATA FOR 2" ADJUSTABLE HYDROCYCLONE

Table B.1 - Steady State Testing with 2" Adjustable Hydrocyclone without UF Tip

Test Run	Feed Density, ppg	UF Density, ppg	OF Density, ppg	Flow Ratio	Head Pressure, psig
1	9.50	9.90	8.50	0.71	54
2	9.60	10.00	8.50	0.73	54
3	9.70	9.90	8.50	0.86	54
4	9.65	10.00	8.50	0.77	54
5	9.65	9.95	8.40	0.81	56
6	9.70	10.00	8.40	0.81	56
7	9.70	9.90	8.35	0.87	56
8	9.65	9.90	8.40	0.83	56
9	9.70	10.00	8.50	0.80	56
10	9.80	10.30	8.50	0.72	57
11	9.90	10.30	8.50	0.78	57
12	9.90	10.30	8.50	0.78	57
13	10.00	10.30	8.50	0.83	57
14	9.70	9.90	8.70	0.83	34
15	9.70	9.90	8.70	0.83	34

Table B.2 - Flow Split Testing with 2" Adjustable Hydrocyclone

Test Run	OF Lvl., gal.	UF Lvl., gal.	Q, gpm	Time, sec.	Flow Ratio	Head Pressure, psig
1	9	34	32.3	80	0.791	59
2	9	34	32.3	80	0.791	57
3	9	34	32.3	80	0.791	58

Table B.3 - Single Pass Flow Split Testing with 0.27" and 0.37" UF Tips

Tip Size, in.	OF Lvl., gal.	UF Lvl., gal.	Q, gpm	Time, sec.	Flow Ratio	Head Pressure, psig
0.27	35.5	5	28.6	85	0.12	58
0.37	31	8.5	27.9	85	0.22	62
0.37	30	8	28.5	80	0.21	62
0.37	30	9	29.3	80	0.23	53
0.37	30	9	29.3	80	0.23	55

Table B.4 - Steady State Testing Results for 0.27" and 0.37" UF Tips

Tip Size, in.	Feed Mud, ppg	UF Mud, ppg	OF Mud, ppg	Head Press, psig	Flow Ratio
0.27	10.2	18.95	9.15	58	0.11
0.27	10.2	19.25	9.1	58	0.11
0.37	10.4	16.9	8.75	58	0.20
0.37	10.35	17.0	8.75	62	0.19
0.37	10.45	15.45	9.0	61	0.22
0.37	10.45	15.65	8.9	62	0.23
0.37	10.3	15.3	8.8	60	0.23
0.37	10.3	15.5	8.8	61	0.22
0.37	9.85	14.0	8.6	56	0.23
0.37	9.15	11.3	8.4	56	0.26
0.37	9.45	12.1	8.5	56	0.26

Table B.5 - Densities and Flow Splits from 0.22", 0.255" and 0.274" UF Tips

Tip size, in.	Feed Mud, ppg	UF Mud, ppg	OF Mud, ppg	Mass Balance Flow Ratio	OF Lvl., gal.	UF Lvl., gal.	Tank Level Flow Ratio
0.22	9.3	17.8	8.7	0.066	51	4	0.073
0.22	9.3	17.9	8.6	0.075	51	4	0.073
0.255	9.3	15.9	8.55	0.102	50.5	6	0.106
0.255	9.3	15.9	8.55	0.102	51	6	0.105
0.274	9.4	16.0	8.65	0.102	54.5	7.5	0.121
0.274	9.4	16.15	8.6	0.106	54	7	0.115

Table B.6 - Test Data for Multi-Regression Equation 6.4

Feed Temp., F	Feed Mud Density, ppg	UF Mud Density, ppg	OF Mud Density, ppg	UF Outlet Dia., in.	Pressure, psig
114	10	18.90	9.10	0.19	58
102	9.7	17.40	9.00	0.19	58
103	10	17.70	9.20	0.19	58
109	10.2	18.95	9.15	0.27	58
116	10.2	19.25	9.10	0.27	58
112	10.4	16.90	8.75	0.37	58
111	10.35	17.00	8.75	0.37	62
91	10.45	15.45	9.00	0.37	61
96	10.45	15.65	8.90	0.37	62
98	10.3	15.30	8.80	0.37	60
104	10.3	15.50	8.80	0.37	61
113	9.85	14.00	8.60	0.37	56
116	9.15	11.30	8.40	0.37	56
116	9.45	12.10	8.50	0.37	56
100	9.4	18.5	8.7	0.19	55
104	9.40	18.2	8.8	0.19	55
100	9.80	18.9	9.1	0.19	55
90	9.3	17.8	8.7	0.22	55
106	9.3	17.9	8.6	0.22	55
108	9.3	15.9	8.55	0.255	55
104	9.3	15.9	8.55	0.255	57
110	9.4	16.0	8.65	0.274	57
111	9.4	16.15	8.6	0.274	56
99	9.4	15.7	8.75	0.274	55

Table B.7 - Test Data for Flow Ratio Equation 6.5

UF Outlet Dia., in.	UF Level, gal.	OF Level, gal.	Total Flow, gal.	Flow Ratio
0.19	3	35	38	0.079
0.19	3	37	40	0.075
0.27	5	35.5	40.5	0.123
0.37	8.5	31	39.5	0.215
0.37	9	30	39	0.231
0.37	9	30	39	0.231
0.19	3.5	49	52.5	0.067
0.19	3.5	50	53.5	0.065
0.22	4	51	55	0.073
0.22	4	51	55	0.073
0.255	6	50.5	56.5	0.106
0.255	6	51	57	0.105
0.274	7.25	54.5	61.75	0.117
0.274	7	54	61	0.115

VITA

John Shelton is a native Hoosier from Marion, Indiana. John served in active duty in the United States Navy for six years, serving four years on the combat ship U.S.S. Enterprise. He later worked in various steam and diesel engineering plants, both shipboard and onshore. John is a graduate of Purdue University School of Technology. John began his studies at Louisiana State University in June of 2003. His technical interests are drilling fluid and heat and power systems.